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NATIONAL WEATHER SERVICE
NATIONAL METEOROLOGICAL CENTER

OFFICE NOTE 355

VERIFICATION TESTS OF THE ETA MODEL, OCTOBER-NOVEMBER 1988

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1. The eta model

Thge sigma system introduced at the early stage of numerical weather prediction has enabled a simple representation of the effect of mountains and has become almost universally accepted. Concern has however persisted over the possibility of large errors in calculation of the pressure gradient force over steep terrain slopes in some situations, and errors also may occur or are known to occur in the horizontal advection and lateral diffusion. Experience shows that sigma system models do indeed have difficulties with very steep mountains thus it is a common practice to smooth terrain elevations before they are incorporated into NWP models. This however reduces the barrier effect of model mountains and/or the ability of the model to capture the influence of smaller scale terrain features.

A technique proposed a few years ago to circumvent these difficulties (Mesinger 1984) is the use of the eta coordinate which is a generalization of the sigma coordinate but permits step-like representation of mountains and quasi-horizontal coordinate surfaces. The "minimum physics" eta model developed at the University of Belgrade and at the Geophysical Fluid Dynamics Laboratory, Princeton (Mesinger et al. 1988a), has been recoded at NMC for efficient vectorization and subsequently subject to comprehensive further development and testing. In particular, during 1987 a comprehensive physics package was added to the model (Janjić and Black 1987). The model formulation differs from that of NMC's regional operational Nested Grid Model (Phillips 1979; Hoke 1984) in a number of ways in addition to its use of the eta coordinate, as follows.

- Space differencing schemes used are designed to minimize the need for artificial noise-control mechanisms. This is primarily achieved by a different horizontal grid (Arakawa E as opposed to D) and a momentum advection scheme (Janjić 1984) which strictly controls the false energy cascade toward smaller scales.

- Forward-backward (split-explicit) time differencing is applied for the adjustment terms, which along with splitting of the adjustment and the advection terms and the rotation of the spherical coordinates permits adjustment time steps more than 3 times longer than those used by the NGM for about the same horizontal grid distance.

- More advanced and/or different formulation is used for some of the major components of the physical package including the Mellor-Yamada level 2.5 turbulent exchange (Mellor and Yamada 1974, 1982) and Betts convective parameterization scheme (Betts 1986; Betts and Miller 1986). These, however, may be or have been (the Betts convection scheme) written in a "plug compatible" form so that after being tested in the eta model they can also be used in other models.

The lateral boundary treatment, choice of the integration region, and the coding approach are still other aspects in which the eta model differs from the NGM. The lateral boundaries are prescribed in a one-way mode so that when used for NWP the boundary conditions have to be provided by a larger scale model. While this represents a restrictive feature it also enables the model to be run for an extended time as a nested model. The integration region is defined by a specification of its central longitude and latitude and the extension in terms of the rotated longitude and latitude. The model is thus easily run on any region of interest. Finally, for portability and for the ease of a possible change to a next generation computer system the CYBER 205 FORTRAN extensions are either avoided or are used along with an alternate standard ANSI code. The alternate code has been tested by experimental integrations performed outside NMC on two different computer systems.

Preliminary results have been reported on several occasions (Janjić et al. 1988; Black and Janjić 1988; Mesinger et al. 1988b, 1988c) and testing is proceeding along a number of directions. Because the model can switch from the eta to the sigma coordinate mode, direct comparisons between the two can be made. Such eta/sigma mode experiments have indicated an increased noisiness and somewhat higher standard deviation of geopotential height errors of the sigma integrations; an increased cold bias of the sigma compared to the eta mode, throughout or only at mid-troposphere; and some degradation of short-range accuracy of sea level pressure patterns.

Considerable attention has been directed at comparing the performance of the model against that of the NGM when the eta model is set up to use about the same space resolution as the NGM on its innermost grid and to require about the same computational effort with the present coding. These comparisons have been general in scope with emphasis on mean sea level synoptic features, particularly the evolution of cyclones, and on the prediction of precipitation. During the winter of 1987-88 one notable difference was that the NGM was slow in its forecasts of coastal lows significantly more often than was the eta model while centers in the latter were sometimes too intense. Substantial experimentation has been undertaken since that time aimed at refining the Betts convection scheme in the eta model and by late summer 1988 the eta precipitation threat scores of two 14-forecast series tended to be higher than those of the NGM for all rainfall categories greater than 0.25 inches. Precipitation bias scores of the eta model for these two series have also been generally closer to unity than the NGM's.

One pilot experiment done in 1988 was a ten-day nested run of the eta model with lateral boundary conditions supplied by the NMC medium range spectral model (MRF, Sela 1988). At the 6-7 day forecast time of this experiment both the nested eta and the MRF model forecasts substantially underpredicted the eastward propagation speed of a short-wave mid-tropospheric trough over the western and central United States but the eta model's error was only about half that of MRF's. This was associated with an apparent reduction in the sea level pressure errors of the nested eta over the MRF forecast. The nested eta forecast also better maintained the amplitude of the subtropical high at 500 mb over the south and south-eastern United States by avoiding much of the cold bias problem of the MRF model.

A notably difficult forecast to which particular attention was given is that of the severe weather and tornado outbreak of March 1984. This case has also been considered by other investigators (Kocin et al. 1984; Collins and Tracton 1985; Gyakum and Barker 1988). A low that formed over Texas underwent explosive intensification between about 1800 and 2200 UTC 28 March 1984 while propagating to the northeast. As it crossed the southern Appalachians, the low split and formed separate centers. Three centers have been identified on the routine NMC surface analysis. The center east of the Appalachians was associated with 22 tornadoes occurring from about 2130 UTC 28 March to about 0230 29 March along a line extending from northwest South Carolina to northeast North Carolina. A "double resolution" (grid distance about 40 km) eta model forecast was successful in (a) reproducing the three low pressure centers with the two major centers located very close to their analyzed positions, and (b) predicting a 24-hour accumulated precipitation pattern with the 25 mm contour extending into northwest South Carolina parallel to the Tennessee-North Carolina border, and a low precipitation zone along this border, very much as on the verification map (Mesinger et al. 1988b).

Along with these various verification tests the refinement of a number of model features and of pre- as well as post-processing packages has taken place. As of this writing, the most recent changes in the standard model set-up have been made in September 1988. They consisted of a refinement in the specification of the initial specific humidity so as to have it limited to 95 % relative humidity, which was at some time prior to that chosen for the threshold value of the large scale precipitation; and of a redefinition of the model mountains so as to permit the elevation of lake and sea coast (four-point) steps to be rounded to reference interface elevations greater than zero. Following these changes the longest verification series to date has been performed on data of late October-end of November 1988 when 80 consecutive 48 hour forecasts were performed twice daily on data at 0000 and 1200 UTC.

It is the purpose of this note to (1) report on the eta precipitation scores of this test period, (2) summarize results of the 500 mb height errors for the last 30 days of the period, and (3) show two forecast examples again from this period, one of a precipitation forecast and the other of sea level pressure, chosen to include a storm developing while crossing the western mountainous part of the United States. To the extent this is feasible from the practical point of view results will be compared against those of the current regional (NGM) and global (MRF) operational National Meteorological Center's model.

2. The precipitation scores

In statistical evaluation of the considered sample of 80 consecutive forecasts most attention has been given to precipitation scores. Threat and bias scores (e.g., Anthes 1983) were calculated and compared with those of the NGM for the same initial times. Objective analyses of accumulated precipitation are available at each 1200 UTC, that is, once daily for 24-hour periods. Scores were calculated using a verification program comparing the "experimental" (eta) and the NGM forecasts starting at the begining of each 24-hour period, starting 12 hours earlier, and starting 24 hours earlier. The actual number of 24-hour periods that were verified by the program is 2 less than 40 because of the one 24-hour period needed at the beginning to collect the three forecasts for the same verification time, and another day (ending 1200 UTC 14 November) which was excluded as a result of archiving problems.

This nevertheless being a large volume of data, concentrating on a reduced sample in ways which could produce information of most interest seems desirable. Perhaps one is justified in assuming that if a model is doing better on the second day of the forecast it was doing better also on the first day, or, if this is not so, that a model's weakness in the first day is easier to remove than that in the second day. In addition, days with more intense precipitation would seem to deserve more attention than those with light precipitation. Finally, threat scores were deemed to reflect the accuracy of a model's precipitation forecasts much more than the bias scores.

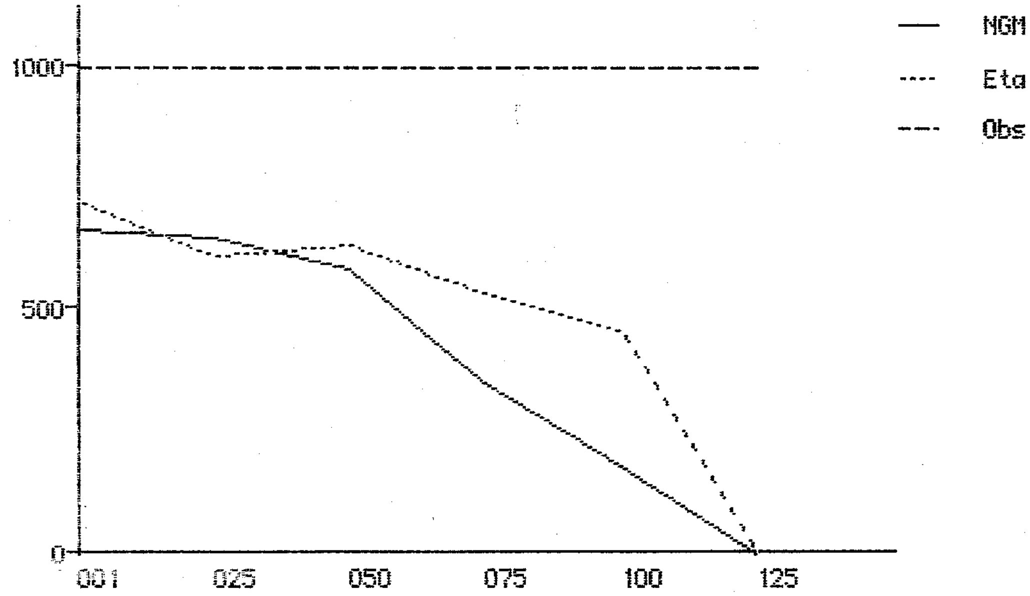
For these reasons, within the mentioned test period 24-48 h forecasts for days with higher precipitation amounts were chosen for inspection. Days with total precipitation on the verification grid (covering about the eastern two-thirds of United States) higher than 30 (relative units) were chosen. There were 12 periods with precipitation amounts higher than this value. For visual inspection, the eta and the NGM threat scores for each of these periods are plotted in Fig. 1 as functions of the threat score category up to that exceeding 1.25 inches. This category of 1.25 inches and greater is the highest category for which all of the 12 periods considered registered verification points.

In one of the 12 periods (ending 1200 UTC 12 November) the NGM scores are slightly better. For two periods it is not obvious which model produced the better forecast. For the remaining nine periods the eta model scores are superior to those of the NGM, typically due to clearly higher scores for the heavier precipitation categories.

The verification program used also calculates the average scores for the three forecast periods. However, because of the 36-day NMC archiving system and a week's lag in precipitation verification, the program could not be used to obtain average scores for the entire 38-day sample. Instead, average scores for four sub-sets of this sample were obtained. They were of various length; the longest was the 26-day sample covering the periods ending at 1200 UTC 5 November - 1200 UTC 1 December (excluding 1200 UTC 14 November). Average values for 0-24 h and for 24-48 h forecasts for this 26-day sample as functions of the score category up to that of 1.75 inches and greater are shown in Fig. 2. Average values for all forecast hours for the same sample are shown as the upper panel of Fig. 3. Average values of the bias scores for all forecasts hours and for the same sample are shown as the lower panel of Fig. 3.

In each of the three plots of the average threat scores shown, the NGM shows slightly higher scores for the 0.01 inches category. For the larger

Ending 1200 UTC 5 November (63.9):



Ending 1200 UTC 6 November (42.2):

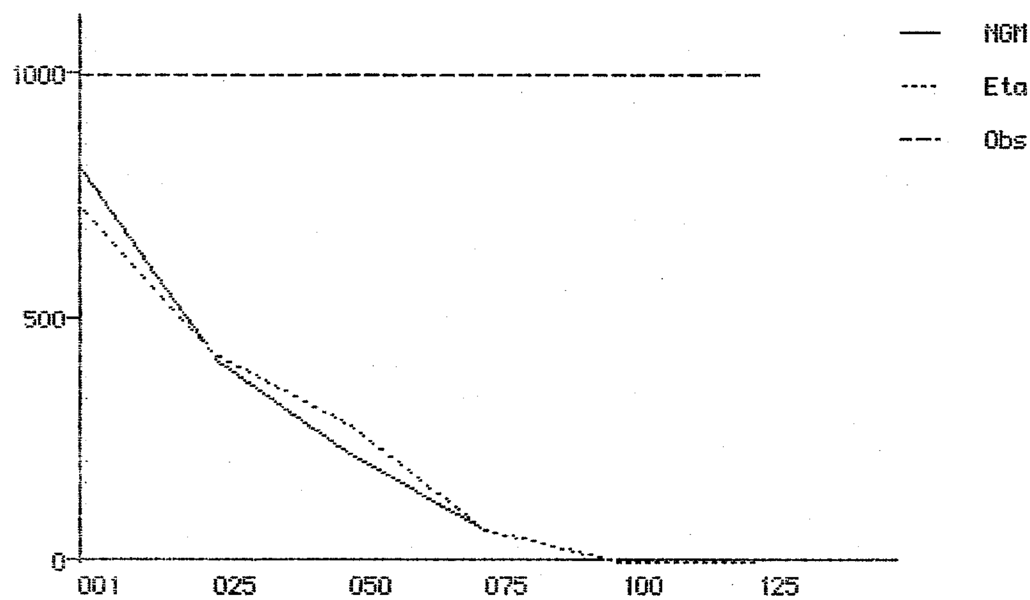
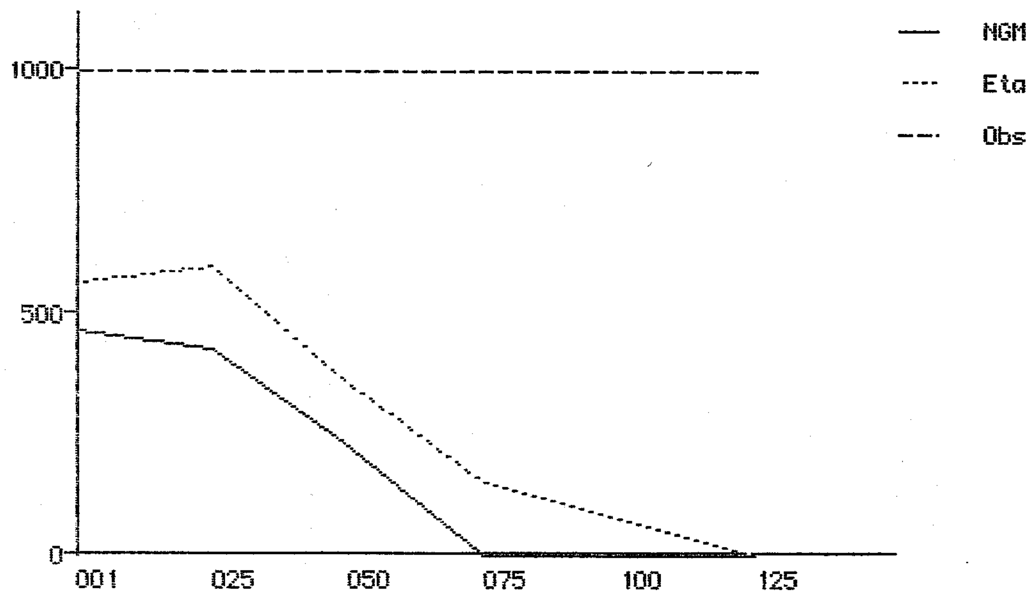
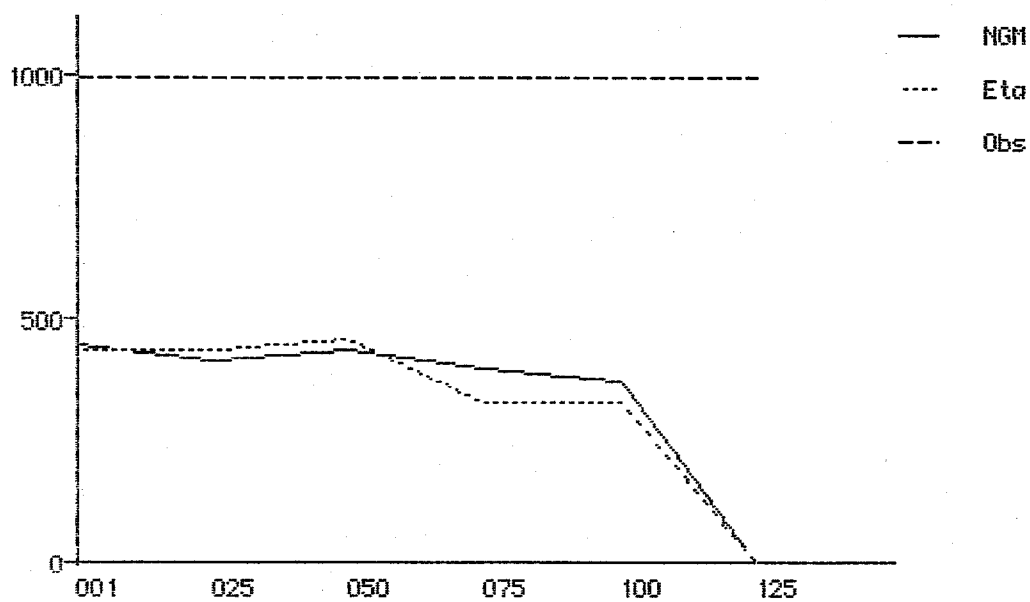


Fig. 1. Threat scores of the NGM and eta 24-48 h forecasts of accumulated precipitation for the 12 periods of highest 24 h precipitation ending at 1200 UTC within the period 24 October through 1 December 1988 with the exception of 14 November (38 24-hour periods). Categories shown in 1/100s of an inch, and threat scores shown x1000. Precipitation amount, in relative units, shown in parentheses. (Continued on following pages)

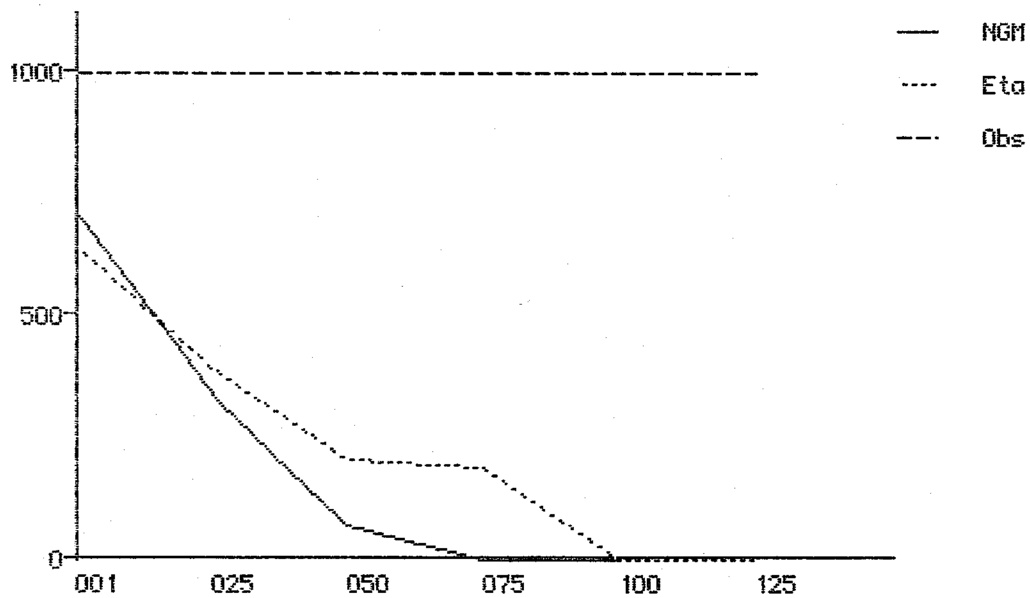
Ending 1200 UTC 10 November (30.4):



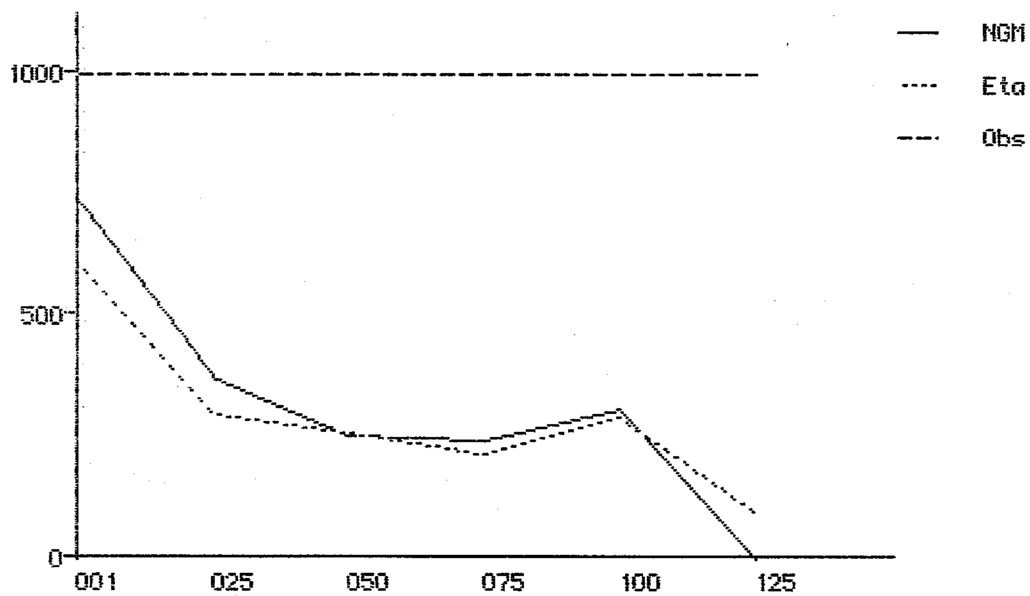
Ending 1200 UTC 12 November (30.6):



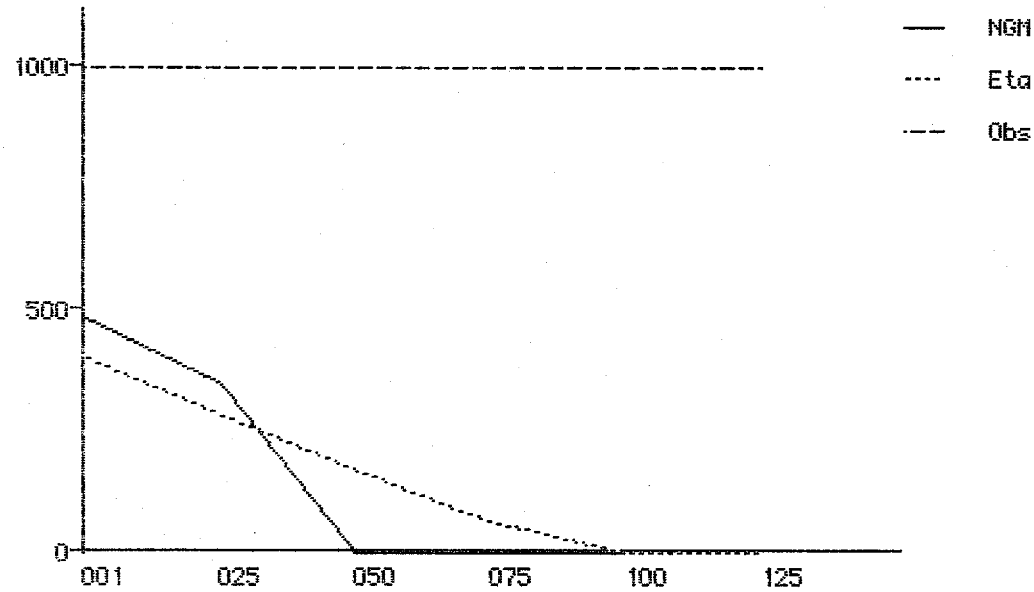
Ending 1200 UTC 13 November (37.6):



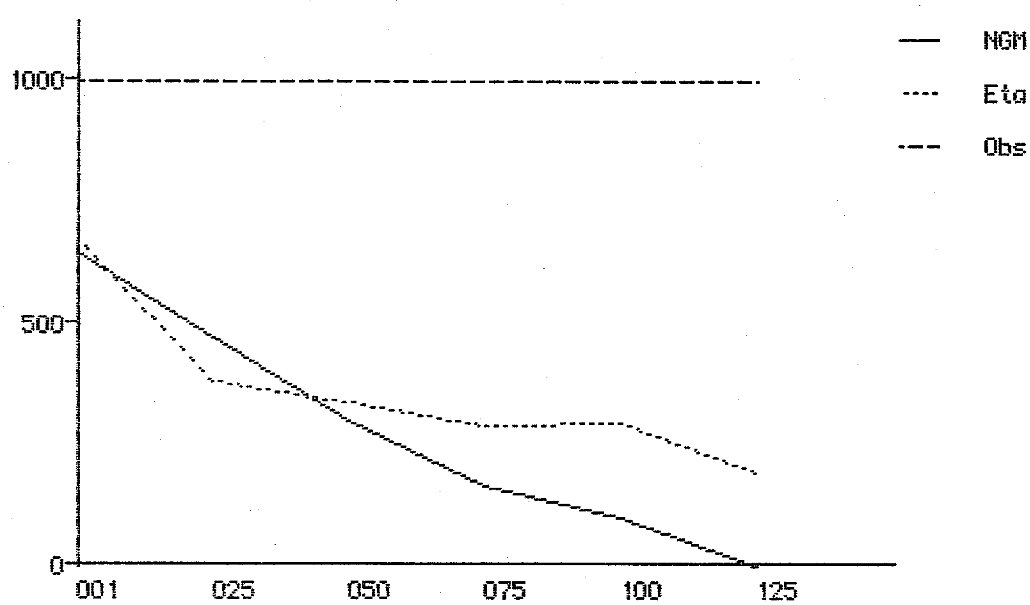
Ending 1200 UTC 16 November (46.9):



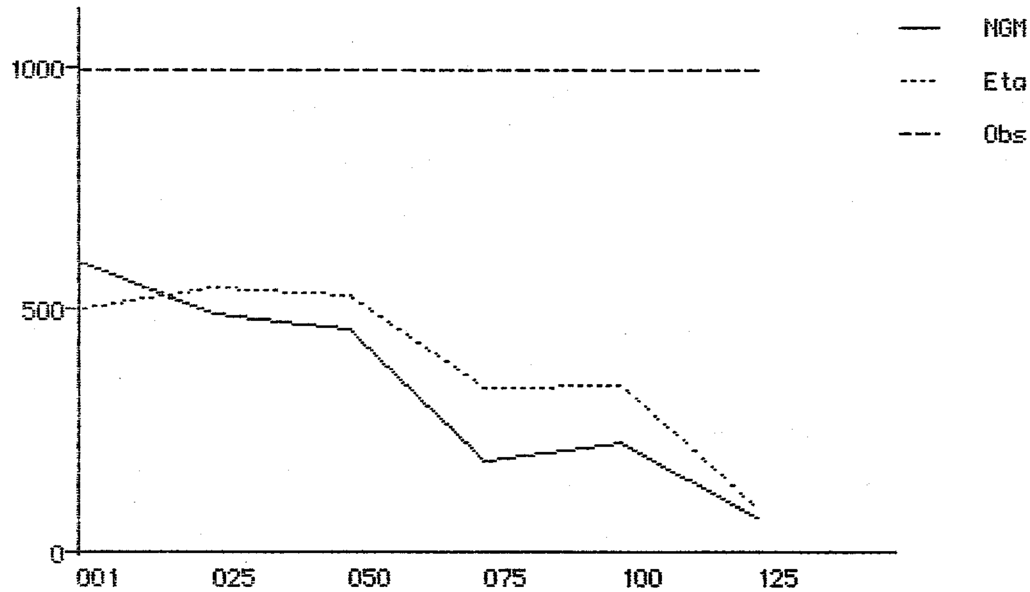
Ending 1200 UTC 19 November (38.0):



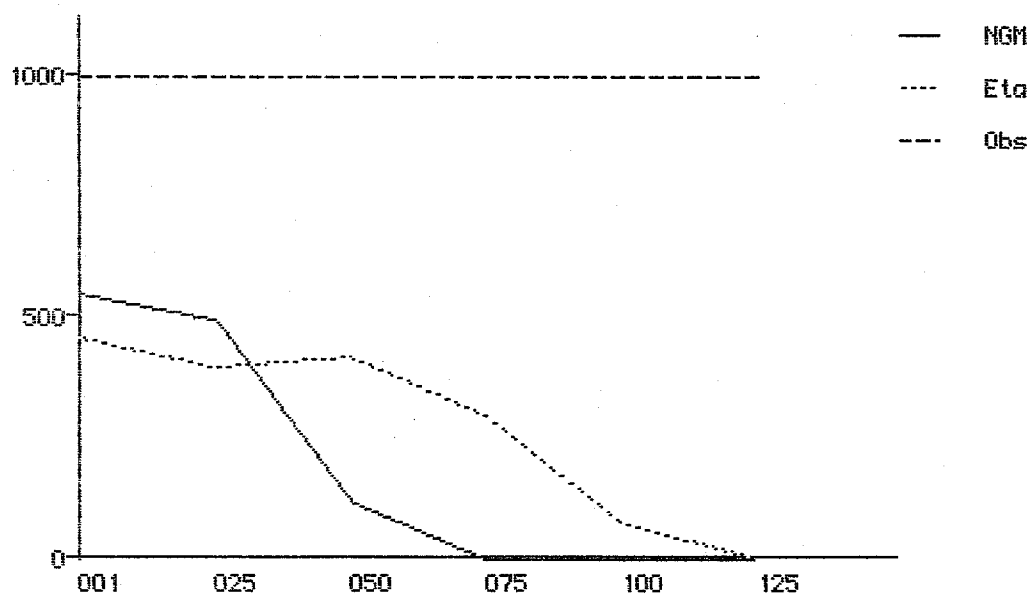
Ending 1200 UTC 20 November (84.1):



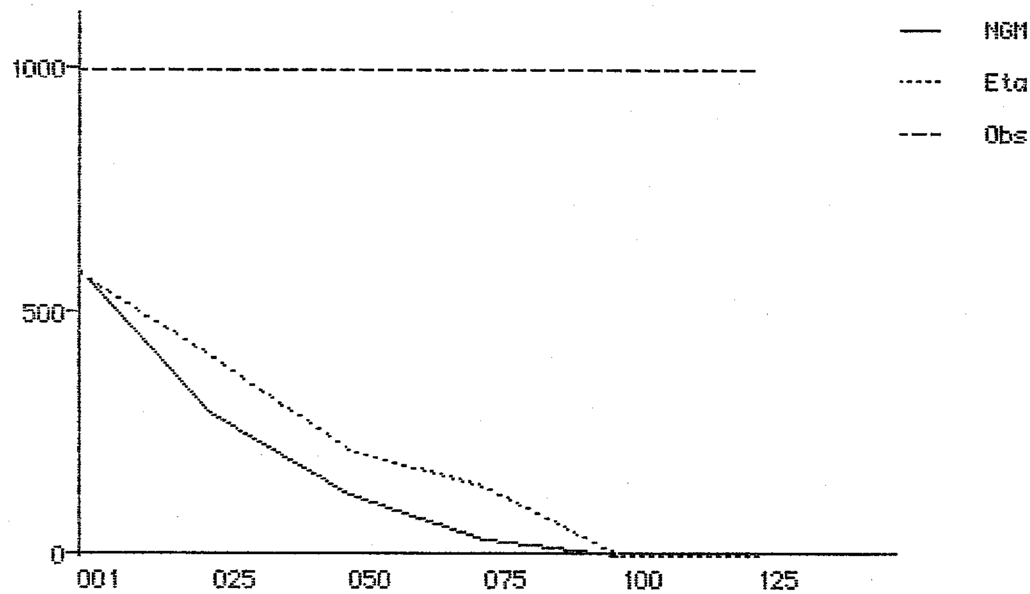
Ending 1200 UTC 21 November (38.9):



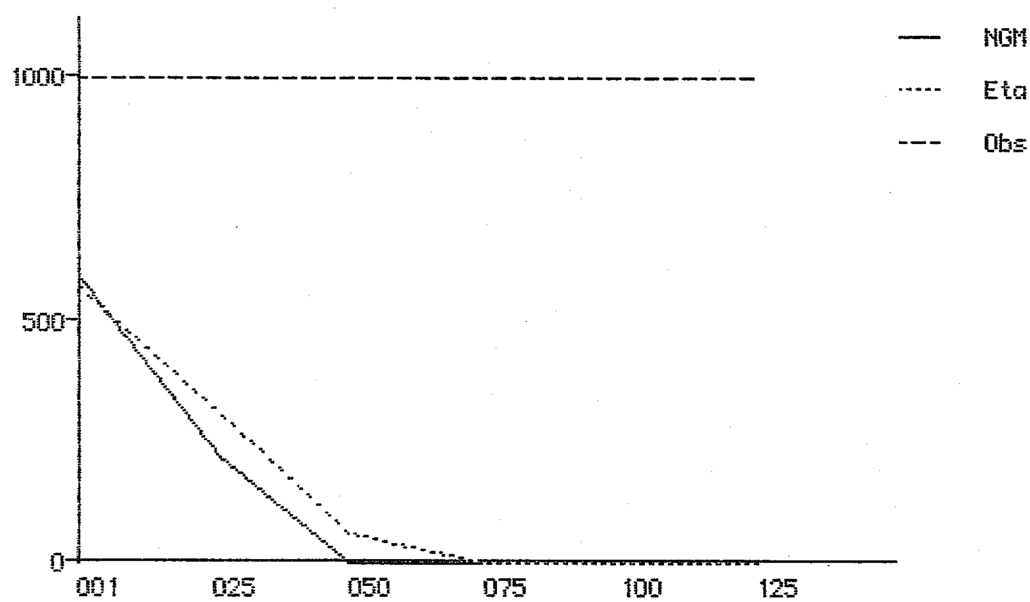
Ending 1200 UTC 26 November (37.1):



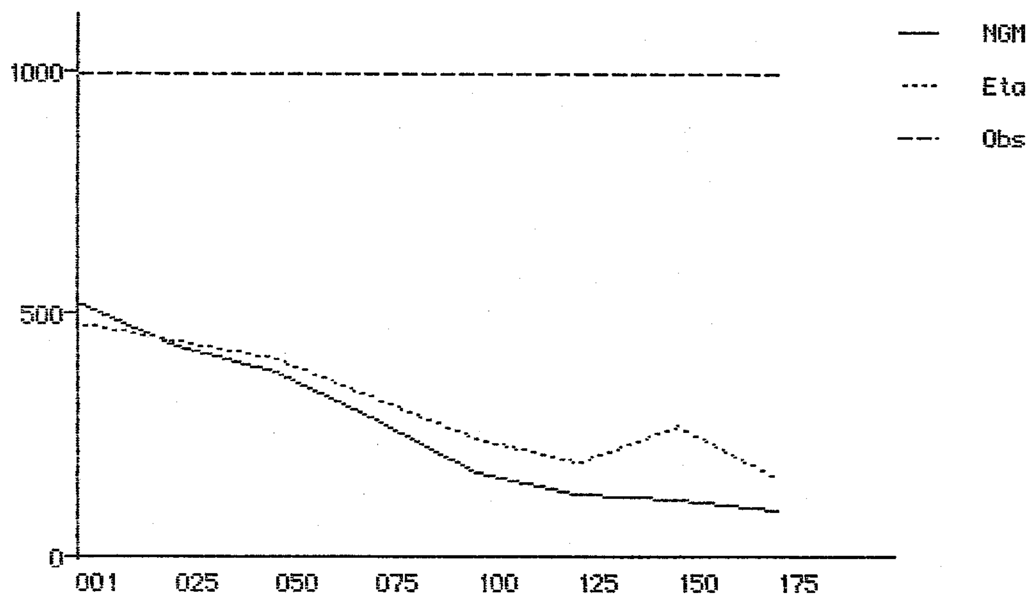
Ending 1200 UTC 27 November (48.1):



Ending 1200 UTC 28 November (38.9):



Total for 0-24 h forecasts, 1200 UTC, 5 November - 1 December:



Total for 24-48 h forecasts, 1200 UTC, 5 November - 1 December:

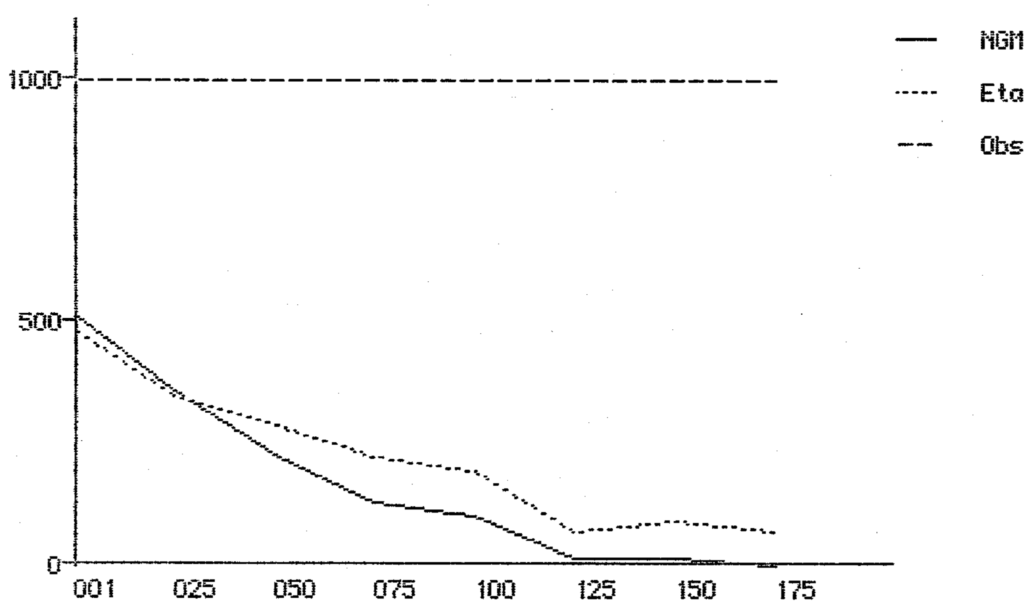
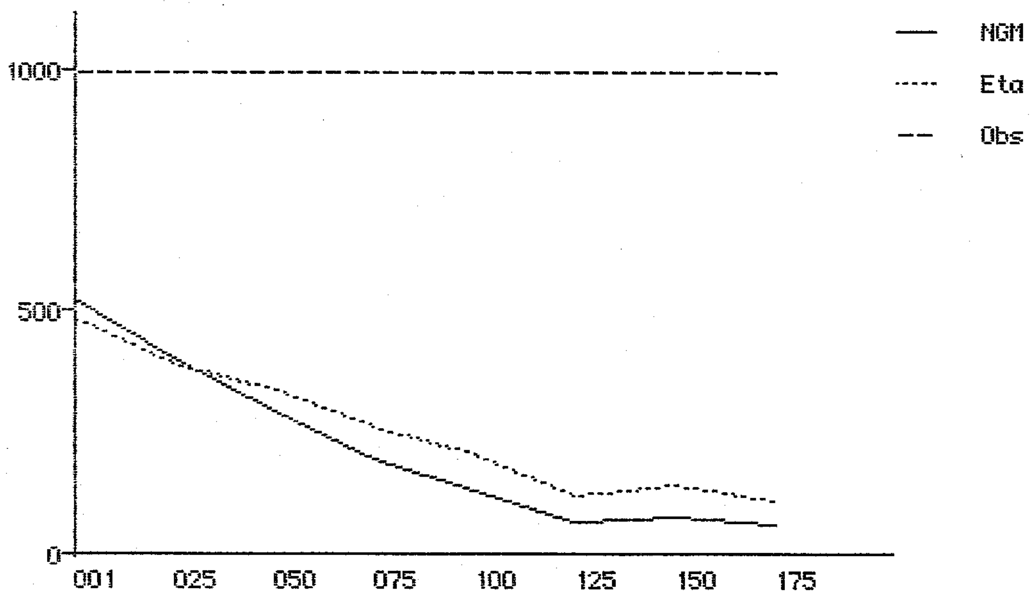


Fig. 2. Average threat scores of the NGM and eta 0-24 h and 24-48 h forecasts of accumulated precipitation, upper and lower panel, respectively, verifying at 1200 UTC, 5 November - 1 December, exluding 14 November, 1988 (26 24-hour periods). Categories shown in 1/100s of an inch, and threat scores shown x1000.

Threat scores, total for all forecast hours, 1200 UTC, 5 November - 1 December:



Bias scores, total for all forecast hours, 1200 UTC, 5 November - 1 December:

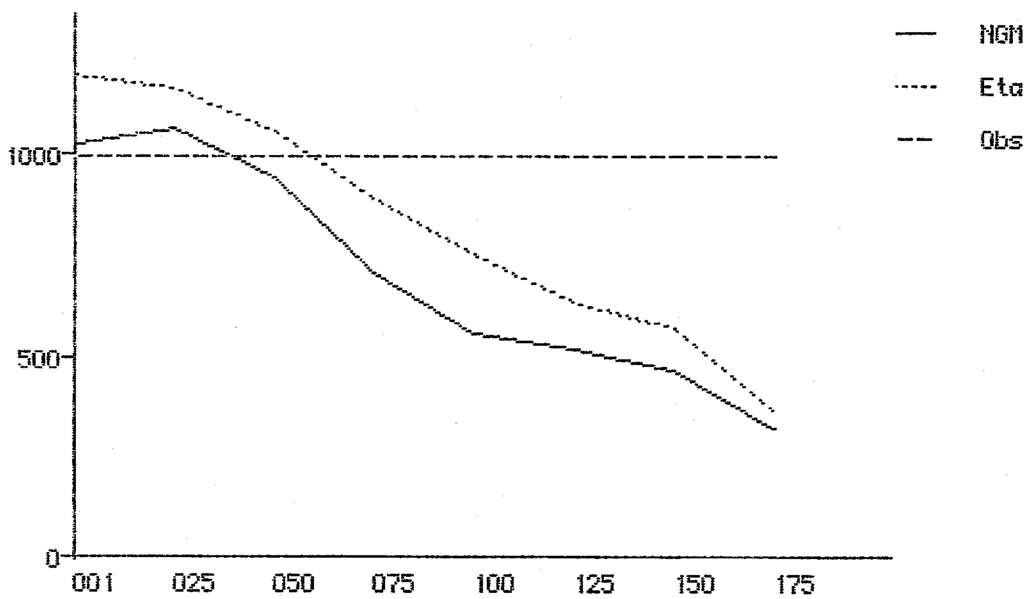


Fig. 3. Threat and bias scores of the NGM and eta 24 h accumulated precipitation forecasts, upper and lower panel, respectively, averaged for all 0-24, 12-36 and 24-48 h forecasts ending at 1200 UTC, 5 November - 1 December, exluding 14 November, 1988 (26 24 h periods). Categories shown in 1/100s of an inch, and threat scores shown x1000.

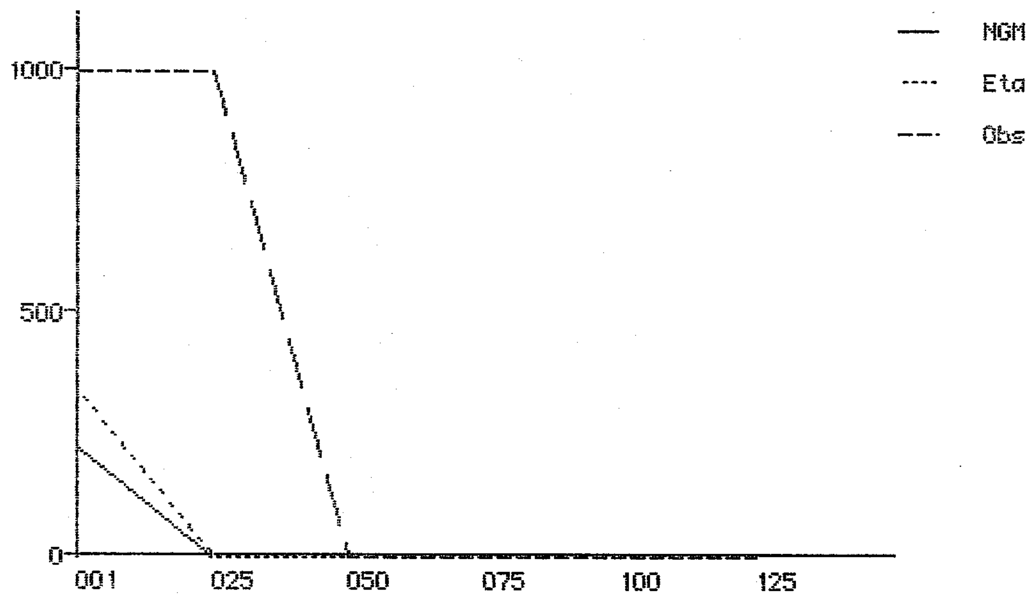
amounts of 1.00 inch and greater in the 0-24 h forecasts and of 0.50 inches and greater in the 24-48 h forecasts and in the overall average (0-24, 12-36, and 24-48 h forecasts) the eta model forecasts yielded scores substantially higher than those of the NGM. Roughly speaking, in the overall average the eta model showed an accuracy which was up to about a factor of two better than that of the NGM for higher precipitation categories in terms of the threat score.

These much improved threat scores did not arise as a result of the eta model forecasting more than observed amounts of intense precipitation. In fact, just as the NGM, the eta model had underforecast the heavier amounts of precipitation (see the bias score plot shown in the lower panel of Fig. 3).

However, one may wonder how are the two models performing for periods of light precipitation? Was the model which verified better for periods of heavy rain perhaps (1) less accurate in days of light precipitation or (2) forecasting excessive precipitation on days when in fact there should be little of it? Regarding the first question, threat scores for days with light precipitation were examined. Plots for the six days of lightest precipitation, half as many days as those of the heaviest precipitation, are shown in Fig. 4. Expressed in terms of threat scores, performance of both models for these periods of light precipitation is unimpressive. No clear advantage of one model over the other is apparent.

As to the second of the two questions, scatter diagrams of the total "observed" vs. 0-24 and 24-48 h forecast precipitation for the two models and for all verifiable 24-hour periods of the 40-day sample is shown in Figs. 5-6. The figures includes the linear least squares fits to the data shown as well as the associated regression equations and correlation coefficients. Some more

Ending 1200 UTC 8 November (6.1):



Ending 1200 UTC 15 November (6.6):

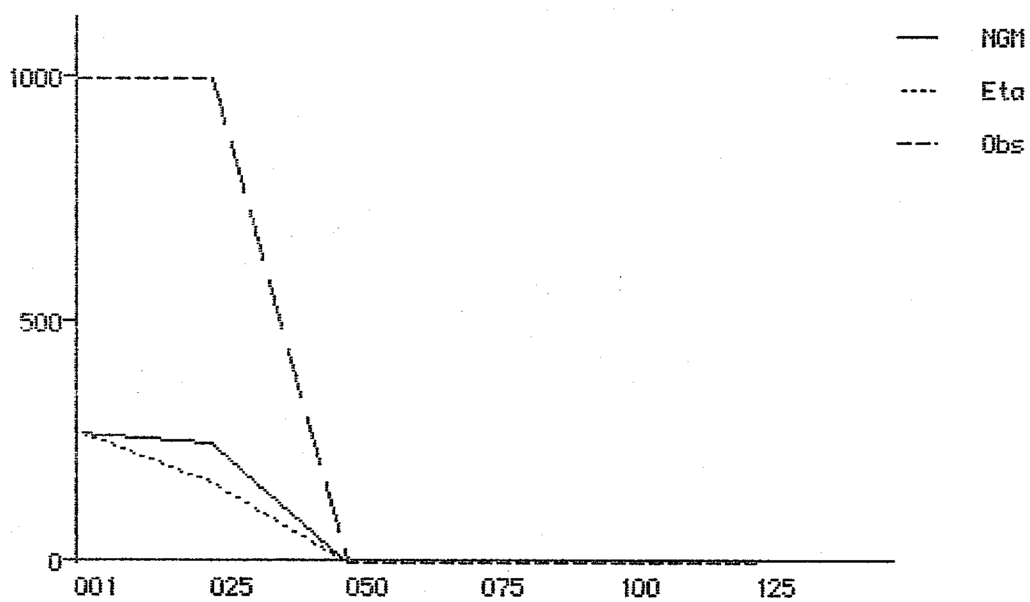
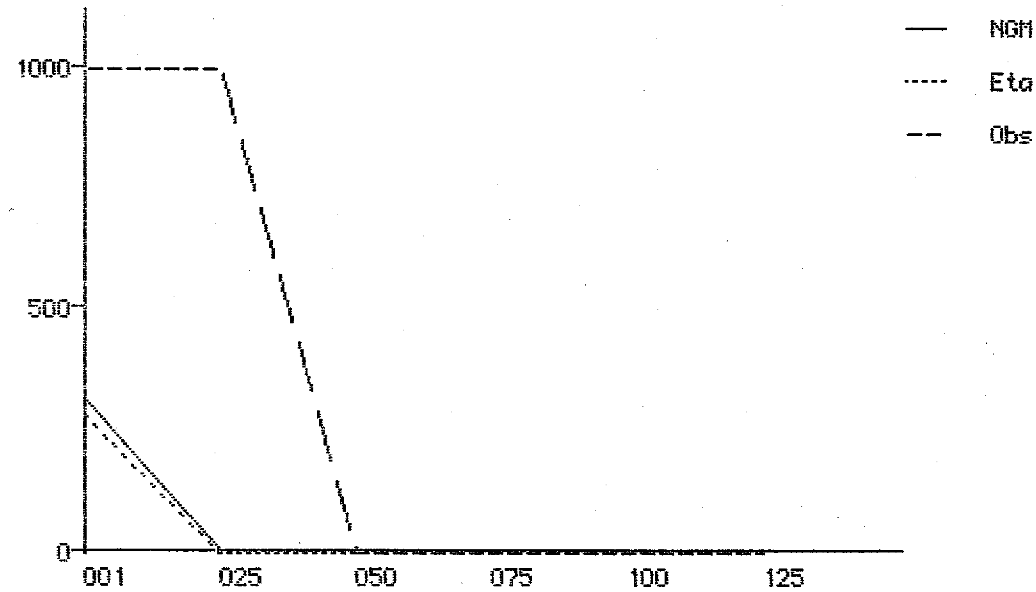
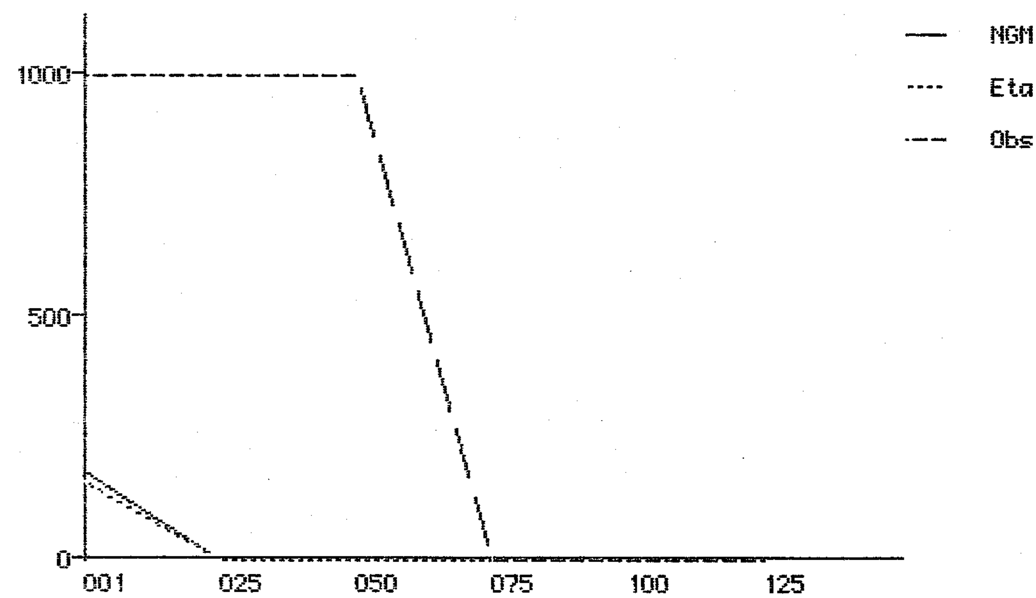


Fig. 4. Threat scores of the NGM and eta 24-48 h forecasts of accumulated precipitation for the 6 periods of lightest 24 h precipitation ending at 1200 UTC within the period 24 October through 1 December 1988 with the exception of 14 November (38 24-hour periods). Categories shown in 1/100s of an inch, and threat scores shown x1000. Precipitation amount, in relative units, shown in parentheses. (Continued on following pages)

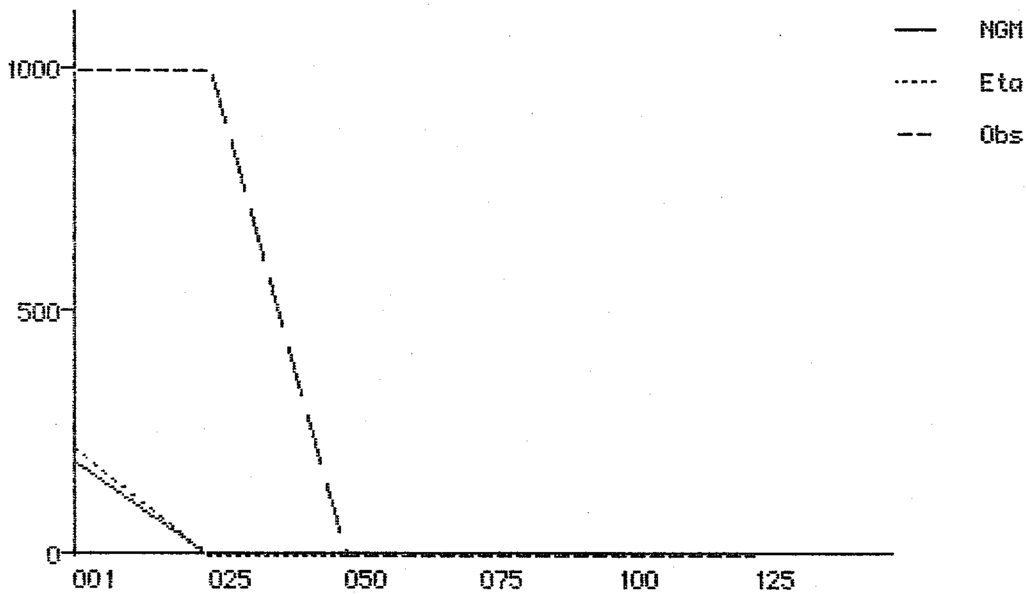
Ending 1200 UTC 22 November (3.6):



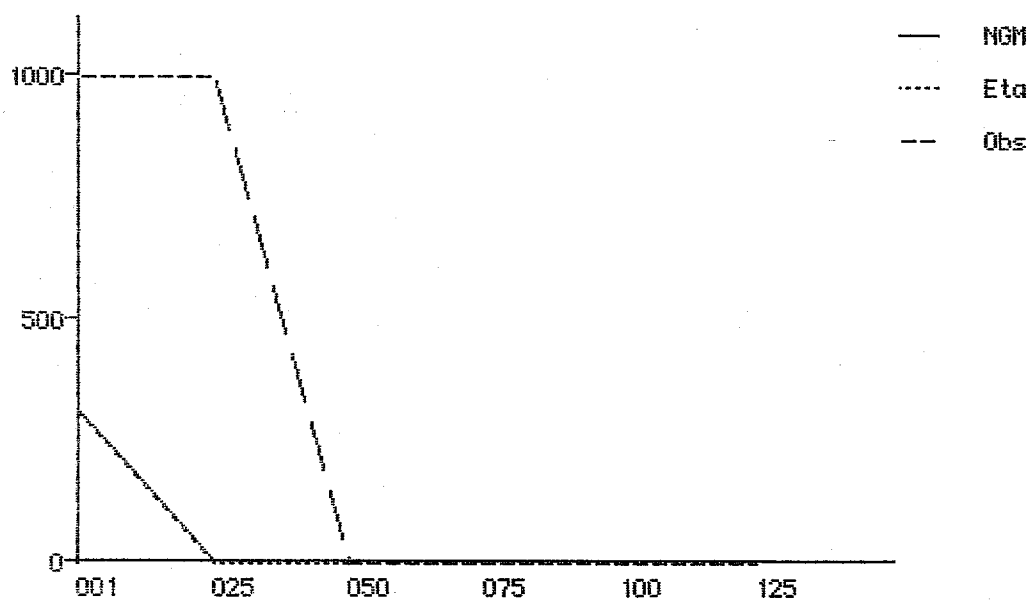
Ending 1200 UTC 25 November (2.3):

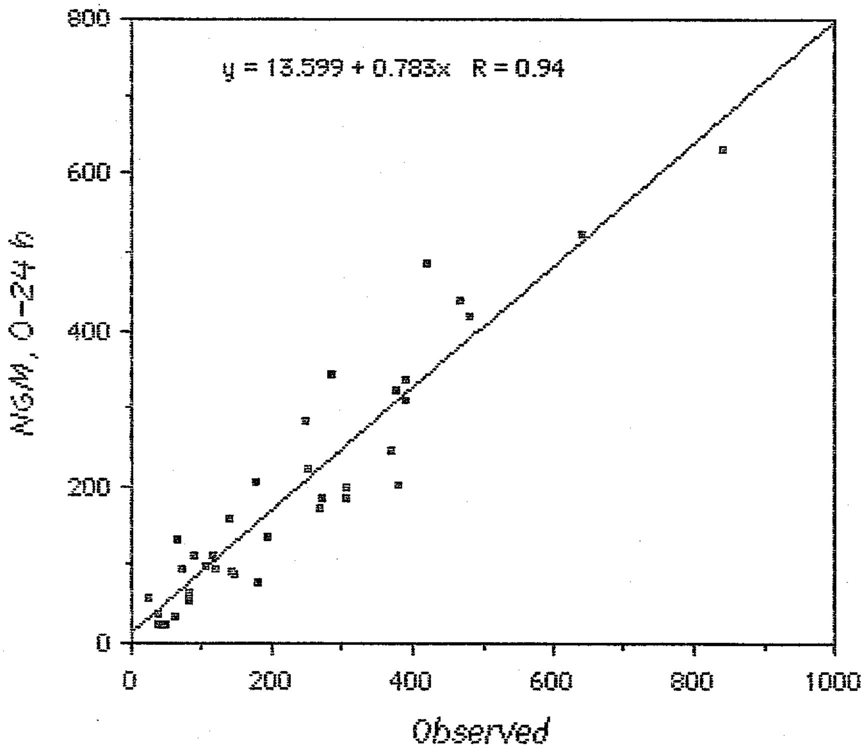


Ending 1200 UTC 30 November (4.6):



Ending 1200 UTC 1 December (3.7):





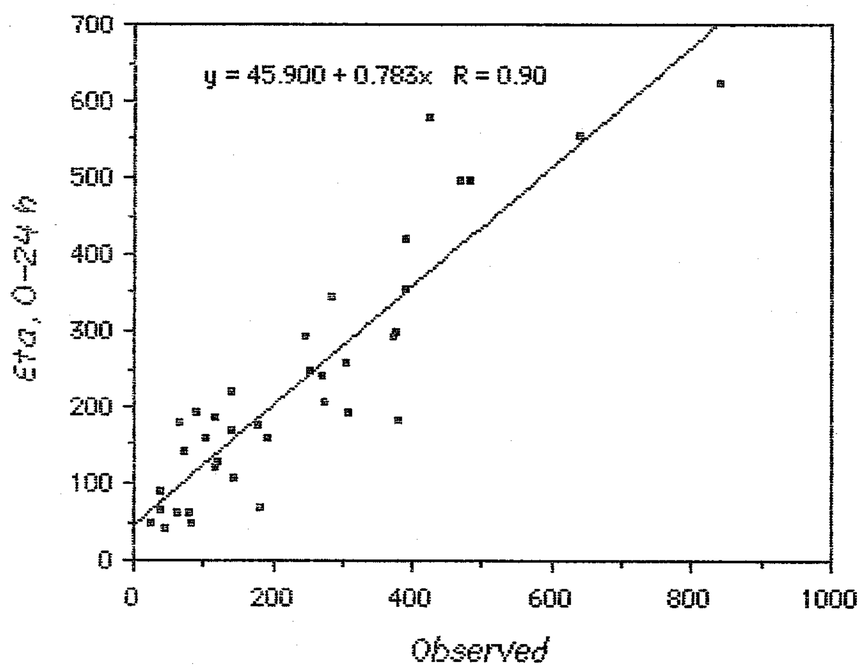


Fig. 5. Observed and 0-24 h forecast accumulated precipitation verifying at 1200 UTC, 24 October - 1 December, excluding 30 October and 14 November, 1988 (37 24-hour periods). Amounts shown are totals over the verification region, in relative units, for the NGM (upper panel) and the eta model (lower panel).

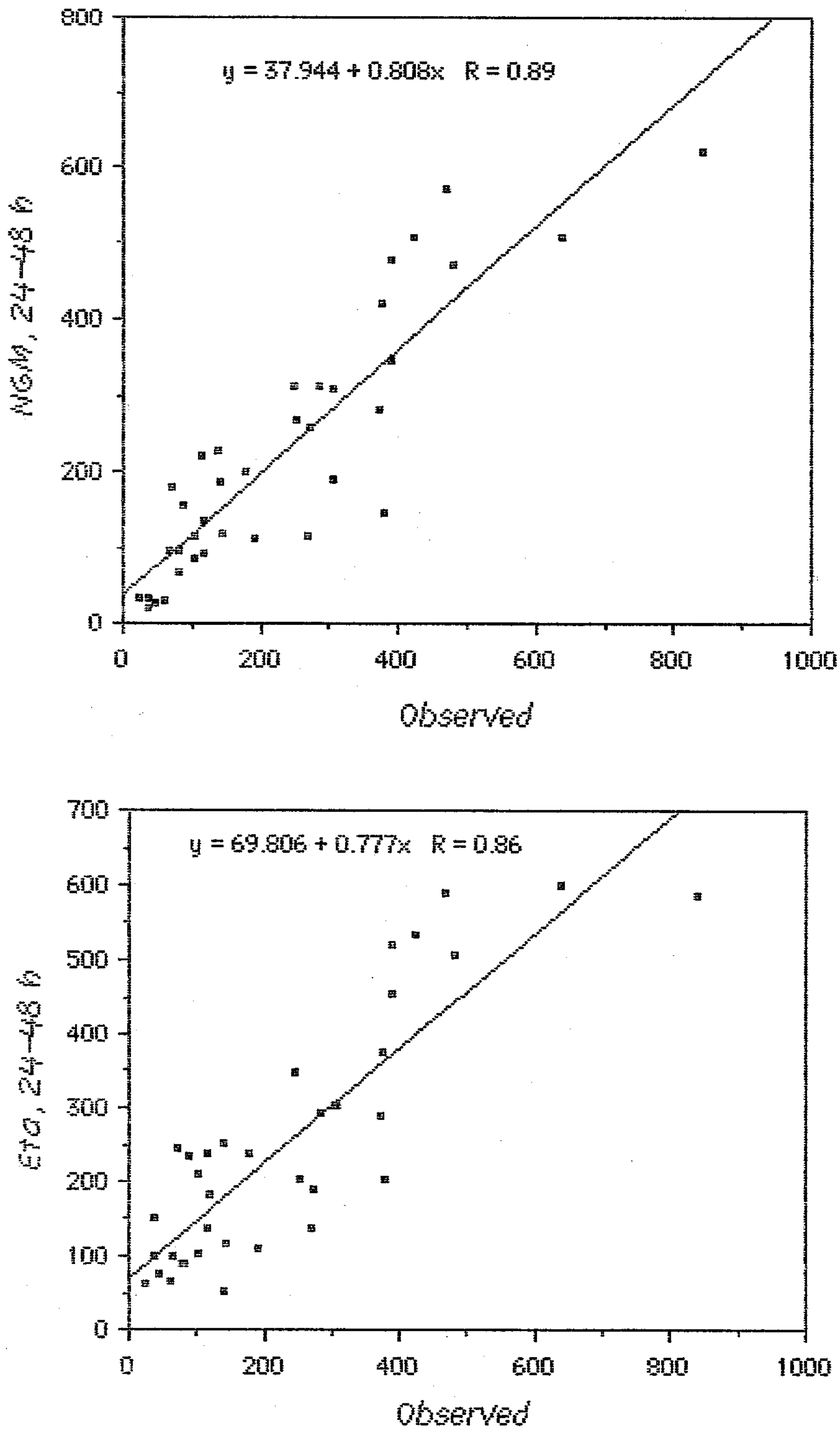


Fig. 6. Observed and 24-48 h forecast accumulated precipitation verifying at 1200 UTC, 24 October - 1 December, excluding 31 October and 14 November, 1988 (37 24-hour periods). Amounts shown are totals over the verification region, in relative units, for the NGM (upper panel) and the eta model (lower panel).

scatter of the eta model total precipitation amounts is seen. Both models, however, exhibit an adequate skill in forecasting the total amount, much better than that of forecasting the location of the precipitation over the verification region.

Still another point of concern can be the statistical significance of threat scores as a function of precipitation threshold in view of the decrease in the frequency of precipitation as the intensity increases. Thus, the actual number of LFM grid boxes with precipitation in various categories within the 26 24-hour periods of Figs. 2-3 could be of interest. These numbers are shown in Table 1. On the other hand, one can also argue that the more intense precipitation although less frequent is an event of more interest than the light precipitation.

Table 1. The total number of LFM grid boxes with precipitation equal and above various thresholds for all forecast hours within the 26 24-hour periods ending at 1200 UTC, 5 November - 1 December, excluding 14 November, 1988

Precipitation threshold, inches	Number of LFM grid boxes
0.01	8895
0.25	2190
0.50	1164
0.75	717
1.00	423
1.25	246
1.50	144
1.75	108

3. The geopotential height errors

For verification of geopotential heights, mean, standard deviation, and total height errors at 500 mb were calculated for a number of subsets of the mentioned 40-day period. Again the overall 40-day average could not be calculated using available programs due to the archiving restrictions. Results for the 30 days of November are shown in Figs. 7-8. This time the comparison also includes the aviation model. It is identical to the MRF model, except that it is run with a shorter data cut-off time (3:45 vs. 6:00 h; Bonner 1988) and at 12- (rather than 24) hour intervals. Since verification against the eta model initial conditions was not possible due to archiving reasons, all three models are verified against the NGM intialized fields which presumably puts the NGM at some advantage over the other two models. As it is, beyond 12 hours the aviation model showed the smallest standard deviation error. With the total rms error dominated by the larger of the mean and the standard deviation error the smallest mean error of the eta model did not offset the standard deviation advantage of the aviation model so that the aviation model also had the smallest total rms error.

Several remarks could be made regarding the height errors displayed. Subsequent to our tests the mean 500 mb height error of the MRF/aviation model has been reduced by approximately 30 % after implementation of changes on 30 November 1988 which have included accounting for model-predicted clouds in the radiation code (NWS Technical Procedures Bulletin No. 383). On the other hand, the aviation errors are calculated following the truncation of T80 results to rhomboidal 30 for storage economy. The truncation could reduce the standard deviation of height errors and they could also be affected by the difference in horizontal resolution of the models. One may also note that the eta model boundary conditions in our "standard" runs which include the present test period are derived from the aviation forecasts with 12-hour old initial data. Thus, except for the effect of interpolations the eta model 48-hour errors on the

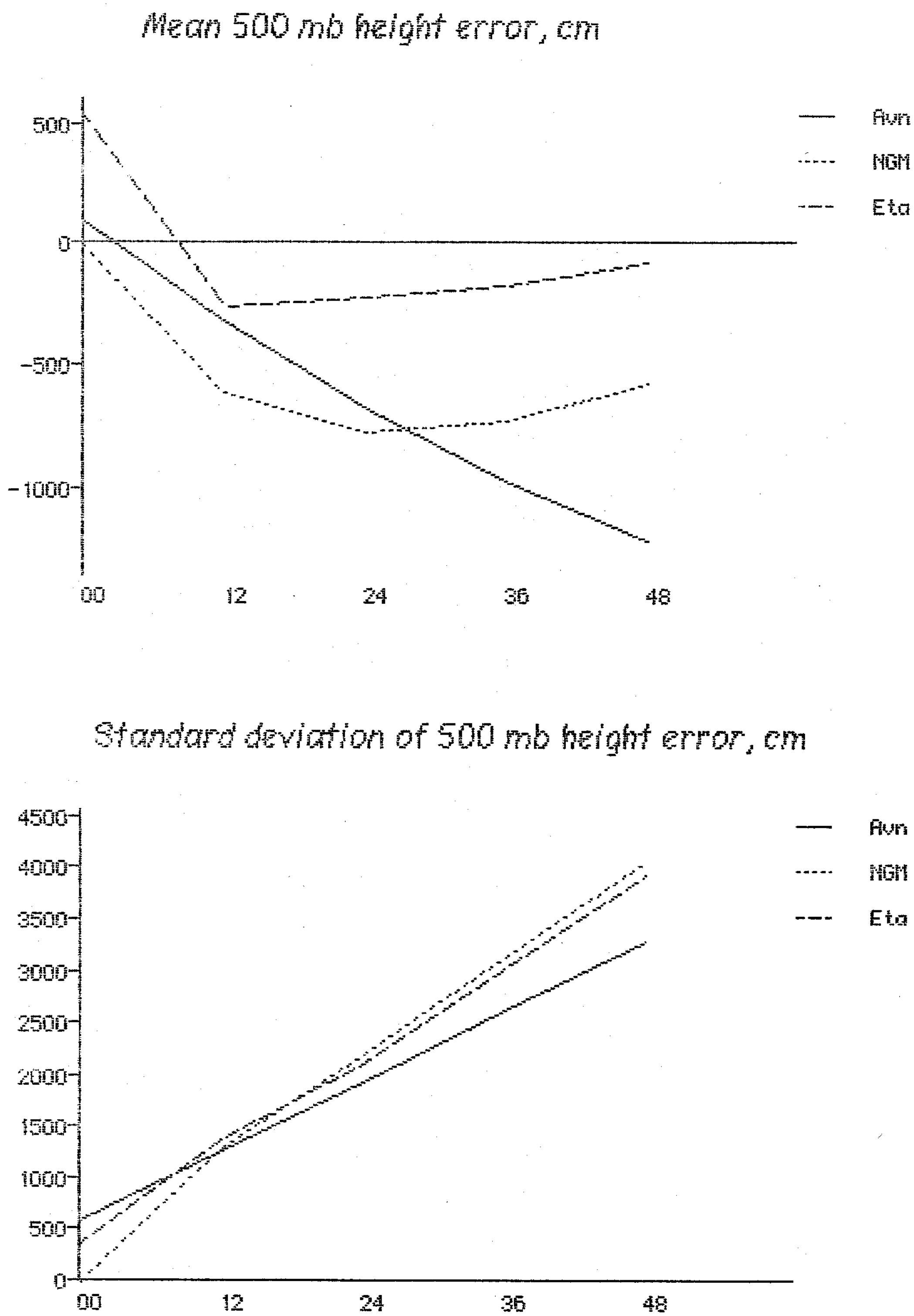


Fig. 7. Mean and standard deviation of the 500 mb geopotential height error, upper and lower panel, respectively. Verification for all three models is done against NGM initialized analyses, on LFM grid. Errors are calculated for land points only. The sample contains 59 aviation, and 60 NGM and eta forecasts, starting at 0000 and 1200 UTC within the 30 days of November 1988.

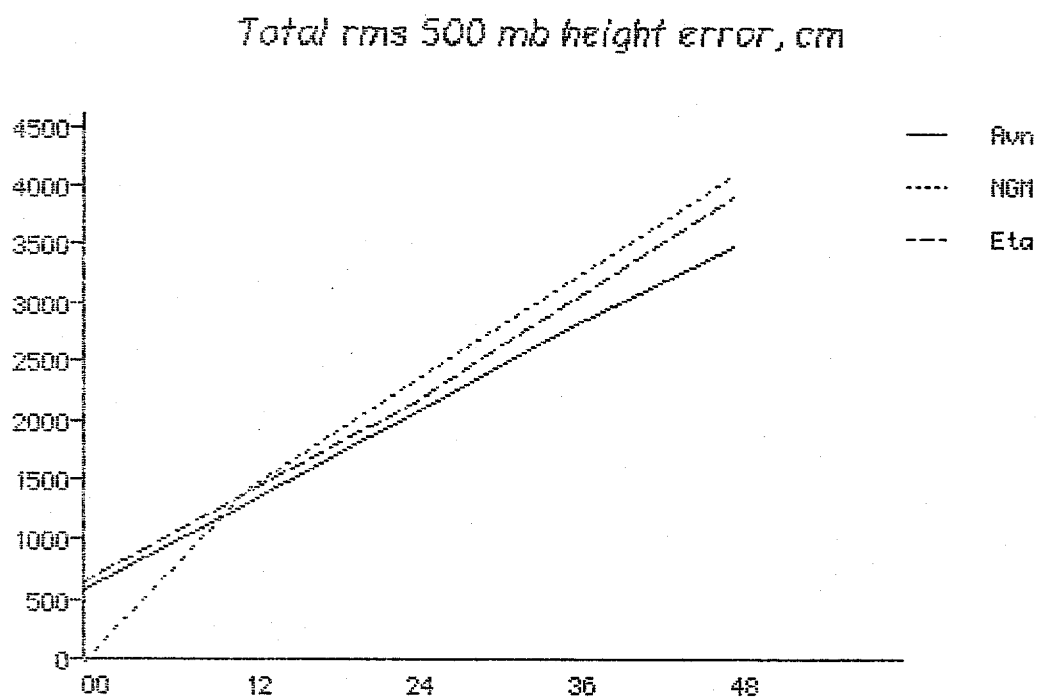


Fig. 8. Total rms 500 mb geopotential height error. Verification for all three models is done against NGM initialized analyses, on LFM grid. Errors are calculated for land points only. The sample contains 59 aviation, and 60 NGM and eta forecasts, starting at 0000 and 1200 UTC within the 30 days of November 1988.

boundary are the same as the 60-hour errors of the aviation model.

4. Forecast examples

In choosing example(s) of precipitation forecasts our original intention was to select, for objectivity, one of the 12 intensive precipitation periods for which the eta model verified best compared to the NGM and one where the opposite was true. However, looking over the threat score plots of Fig. 1 one can note that this is not easily done because among the periods covered (1) there are several for which the eta model scores are higher than those of the NGM to about the same degree and (2) there is no period for which the NGM scores are clearly higher that those of the eta model.

In this situation we will show the precipitation forecasts for the first of the periods of Fig. 1. This happens to be the period of the highest eta model scores for the category of 1.00 inch and greater and also the period of highest sustained scores for both of the models up to and including the category of 0.50 inches and greater. The NGM, the eta model, and the verification accumulated precipitation maps for this period are shown in Fig. 9 as the left hand, the middle and the right hand panel, respectively.

The orientation of the 20 mm contour in the NGM map is just about as that in the verification map but the region it encloses is centered east of that of the verification contour. Thus, the 30 mm contour along the border between Indiana and Ohio at the center of the NGM 20 mm area is located east of the line of highest precipitation on the verification map running across central Tennessee and eastern Kentucky to the tri-state point of Illinois, Indiana and Kentucky. The eta 20 mm area on the other hand is centered very accurately over central Tennessee and then further to the north roughly over Indiana also east of the verification center but not as much as that of the NGM forecast. Further south the location of the NGM line of maximum precipitation roughly along the border between Alabama and Georgia continues to be east of that in the verification map indicated by the 30 mm area over Alabama. The small area of precipitation over 30 mm in the eta map over central Alabama is on the other hand placed well within the 30 mm area in the verification map. The NGM forecast however could be given credit for attempting to reproduce the isolated small area of over 20 mm in the Great Lakes area and only narrowly missing its precise location.

While comparison of features of this kind is certainly of interest the

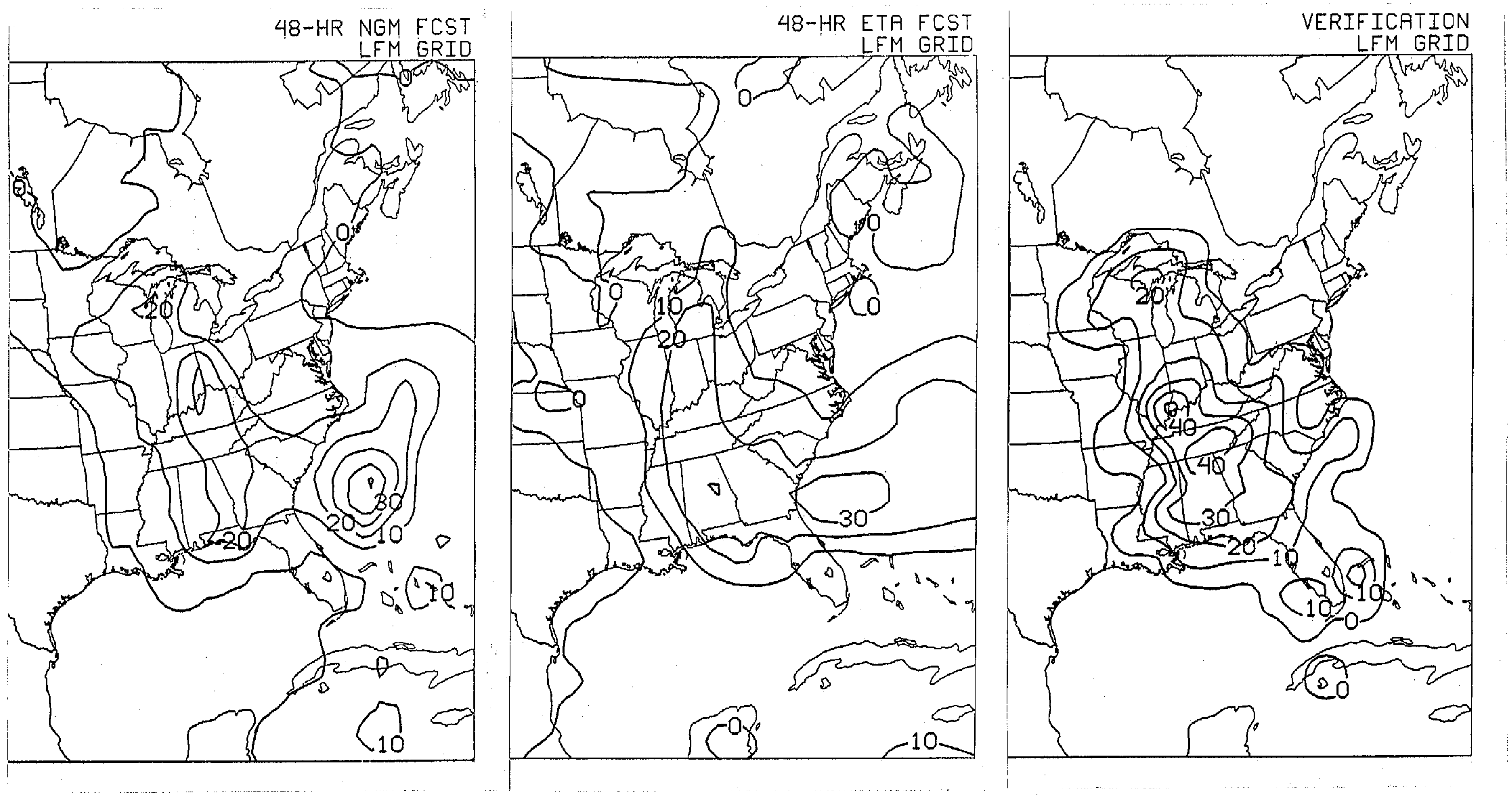


Fig. 9. 24-48 h accumulated precipitation forecasts obtained using the NGM (left hand panel) and the eta model (the middle panel) verifying at 1200 UTC 5 November 1988. NMC verification analysis for the same period is shown in the right hand panel. Amounts shown are in millimeters, and the contour interval is 10 mm.

primary reason for the difference in threat scores seen in Fig 1 for this case is clearly the eta forecast's 20 mm contour in Fig. 9 enclosing an area much closer in size to that observed than does the corresponding NGM contour. Indeed, with 35 (LFM) verification points (boxes) of 0.75 inches (about 19 mm) and greater the eta forecast had 34 points of which 24 verified as opposed to the NGM's 19 points of which 14 verified; a percentage slightly greater than that of the eta forecast. However this is not a common situation. A contrasting example are the forecasts for the 24-hour period ending 1200 UTC 20 November which also was the period of greatest total precipitation and which has probably contributed most to the advantage in scores for higher amounts of precipitation shown by the eta model. In all three of the forecasts for this verification period (in 0-24, in 12-36 and in 24-48 h forecasts) the NGM had higher total amounts of precipitation over the verification region than did the eta model. It also tended to have about the same or even a greater number of verification points in higher precipitation categories. Thus in the 1.25 inches and greater category the 0-24 h NGM forecast had 15 points of which 9 verified as opposed to eta's 16 points of which 15 verified. In the 12-36 h forecast the NGM had 17 points of which 8 verified as opposed to eta's 23 points of which 12 verified. Finally, in the 24-48 h forecast the NGM had 10 points none of which verified as opposed to eta's only 8 points of which 5 have verified however. None of the six forecasts had more points than observed in this category which was 23.

For an example of the sea level pressure forecast we shall show a case chosen to involve a major storm which had crossed the western mountainous part of the United States so that the effects of differences in the treatment of mountains in various models could be emphasized. The storm we chose happened to be associated with an outbreak of 54 tornadoes primarily over Arkansas and Missouri making it the fourth largest on record in terms of the number of tornadoes reported. We shall follow the storm's evolution starting with the initial time of 0000 UTC 14 November 1988. The NMC surface analysis for this time is shown in Fig. 10. A frontal system is seen over a number of western states associated with a main low centered just off the Pacific coast and a secondary center over Nevada along with a multitude of other mesoscale features over surrounding states.

During the next 12 h the frontal system generally moved eastwards and southeastwards so that at 1200 UTC on the NMC surface analysis shown in Fig. 11 three separate centers over the western states are identified (01, 99 and 98) along with two weak centers remaining off the Pacific coast. At that time there was not yet much difference between the eta and the NGM forecasts shown as the lower and the upper panels in Fig. 12, respectively. However the NGM does show generally higher pressures over the southwestern United States more in agreement with the analysis. On the other hand a more accurate depth of the eta model low off the northern California coast should be noted which may have enabled the eta model to show a clearer definition of the trough running southwestwards across southern California. In terms of depth and location the two eta centers of 1001 and of 1000 (mb) are both very near the analyzed centers of 01 and 99 off the two western corners of Wyoming.

One should note that some of this and other detail such as the reduced noise of the eta map in terms of the number of centers printed over mountainous regions is related to the difference in the reduction to sea level used in the two models. A number of options for the reduction to sea level are available in the eta post-processing code. The one used for the map shown in Fig. 12 and for the eta maps in subsequent figures is the so called horizontal (or "relaxation temperature") reduction. It is based on underground virtual temperatures

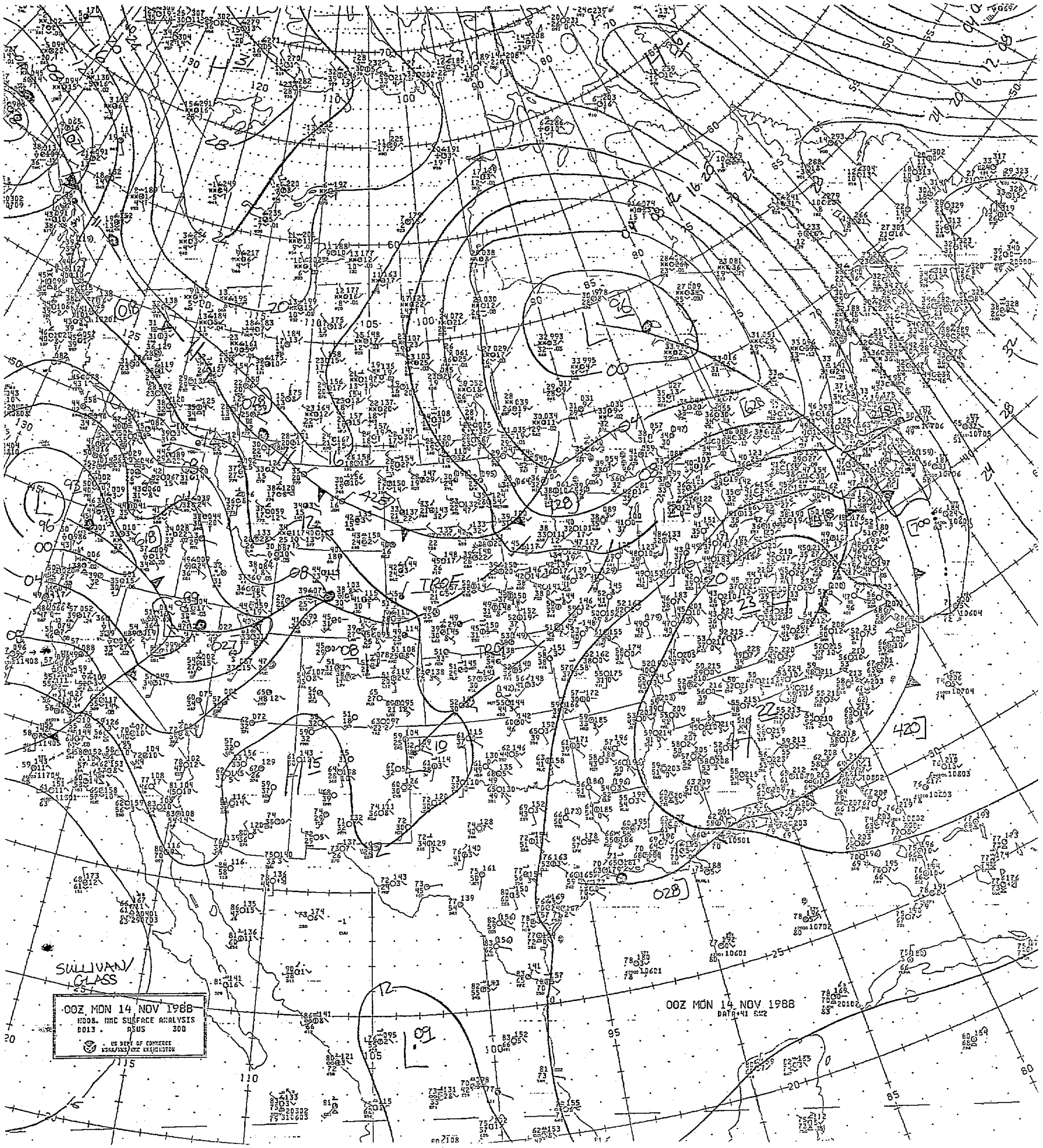


Fig. 10. A section of the NMC surface analysis for 0000 UTC 14 November 1988 (time of the initial conditions of the forecasts shown in the following figures).

computed in each model layer which contains mountains by solving the Laplace equation with virtual temperatures next to the sides of mountains used for boundary conditions. It is our impression that this relaxation temperature method although very different from the one used in synoptic practice nevertheless results in sea level pressure maps which are generally more like the analyzed maps than the maps resulting from a "standard" reduction based on temperatures immediately above ground and a lapse rate of 0.0065 $K\,m^{-1}$.

During the second 12 h the frontal system undergoes changes, which in their large scale features are perhaps not unlike those of a typical frontal baroclinic development but on a smaller scale are associated with a multitude of centers presumably resulting from the complex topography of the region. Thus, on the NMC analysis for 0000 UTC 15 November shown in Fig. 13 three centers are identified along the frontal line and two more in its immediate vicinity. The eta 24 h forecast on the lower panel in Fig. 14 shows two 998 centers, one in eastern Wyoming and another in eastern Colorado somewhat north of the analyzed centers in these states of 97 and 99, respectively. The trough running toward the south-southwest across Arizona which is a major feature of the frontal system of Fig. 13 also appears prominently on the eta forecast map although it is not as sharp as in the analysis. All of this detail is missing on the NGM forecast shown as the upper panel in Fig. 14 which has only a single center in Wyoming a good deal deeper than the 97 Wyoming center on the analysis map. An erroneous pressure gradient over Arizona is seen associated with the lack of the trough seen in the analysis.

Within the third 12 h period the frontal system having mostly crossed the mountains becomes more coherent with a single major center in southeastern Colorado and a secondary center in eastern Nebraska (Fig. 15). There is not much to object to in the eta forecast shown as the lower panel in Fig. 16 except that one might wish to see some ridging of the 1000 and 1004 mb isobars towards the northeastern corner of Colorado and less troughing of the 996 mb isobar into Nebraska. The NGM forecast shown as the upper panel in Fig. 16 is also missing such detail but is also failing to capture the larger scale shape of the system and is placing the center north of its observed position. This position and the depth error are associated with the excessive pressure gradient over eastern Wyoming, almost twice as intense as on the analysis in Fig. 15.

During the final 12 hours of the 48 h period the frontal system perhaps surprisingly again acquires a more complex shape so that now three centers are identified on the NMC analysis shown in Fig. 17 within the low pressure area running from southeastern Kansas to the southeastern corner of Minnesota. The major 89 center is somewhat west of the midpoint of the border between Missouri and Iowa. The eta forecast shown as the lower panel in Fig. 18 fails to identify the two secondary centers but does have the major low center accurately located and captures the troughiness of the 996 mb isobar into northeastern Oklahoma as well as the ridging along the northern border of Kansas indicative of the southern secondary center. The NGM forecast shown in the upper panel of the figure departs further from the observed development in exhibiting excessive deepening by this time in addition to its storm position and shape error. Associated large difference between the NGM and eta pressure gradient patterns and corresponding circulations over Minnesota when compared with the analysis in Fig. 17 over the same region is one feature favoring the eta over the NGM forecast at that time.

Sections of the MRF 24- and 48-hour forecasts for the same initial time are shown in Fig. 19 as the upper and the lower panel, respectively. The MRF as a global model is of course not meant to forecast detail of the kind discussed on the preceding pages; indeed at 24 h the storm over the western states while being very accurately placed does not exhibit all of the detail seen in the eta forecast such as the separate centers in eastern Wyoming and in eastern Colorado and the troughiness into southern Arizona. The excessive depth of the low, 992 mb compared to analyzed 97, might be due to a number of reasons one of which is the reduction to sea level. For example, the two 998 mb centers of the eta map in Fig. 14 both end up with values 4 mb deeper when the "standard" reduction is used. At 48 h over lower terrain the MRF depth of 990 mb is the same as that of the eta forecast and the shape of the storm is very similar. The largest difference between the two forecasts at that time might be in the position of the storm center with the MRF center across Iowa lagging behind the eta center by about 100 km or so. This is of course reflected in differences in pressure gradient patterns over specific areas such as again over Minnesota.

The forecasts which have been discussed in this section were not necessarily chosen to depict characteristics typical of the models but simply to show how they handled individual situations. On a day-to-day basis the differences between the eta and NGM's forecasts tended to be smaller.

5. Summary and plans for further work

For a 40-day series of 80 eta model and NGM 48 h forecasts in October-November 1988 the eta model was substantially more accurate than the NGM in forecasting higher amounts of 24-hour accumulated precipitation of 0.50 inches and greater. The two models seemed about equally accurate in forecasting lighter amounts of precipitation. The greatest relative gain in accuracy of the eta over the NGM forecasts was in the 24-48 h forecast range

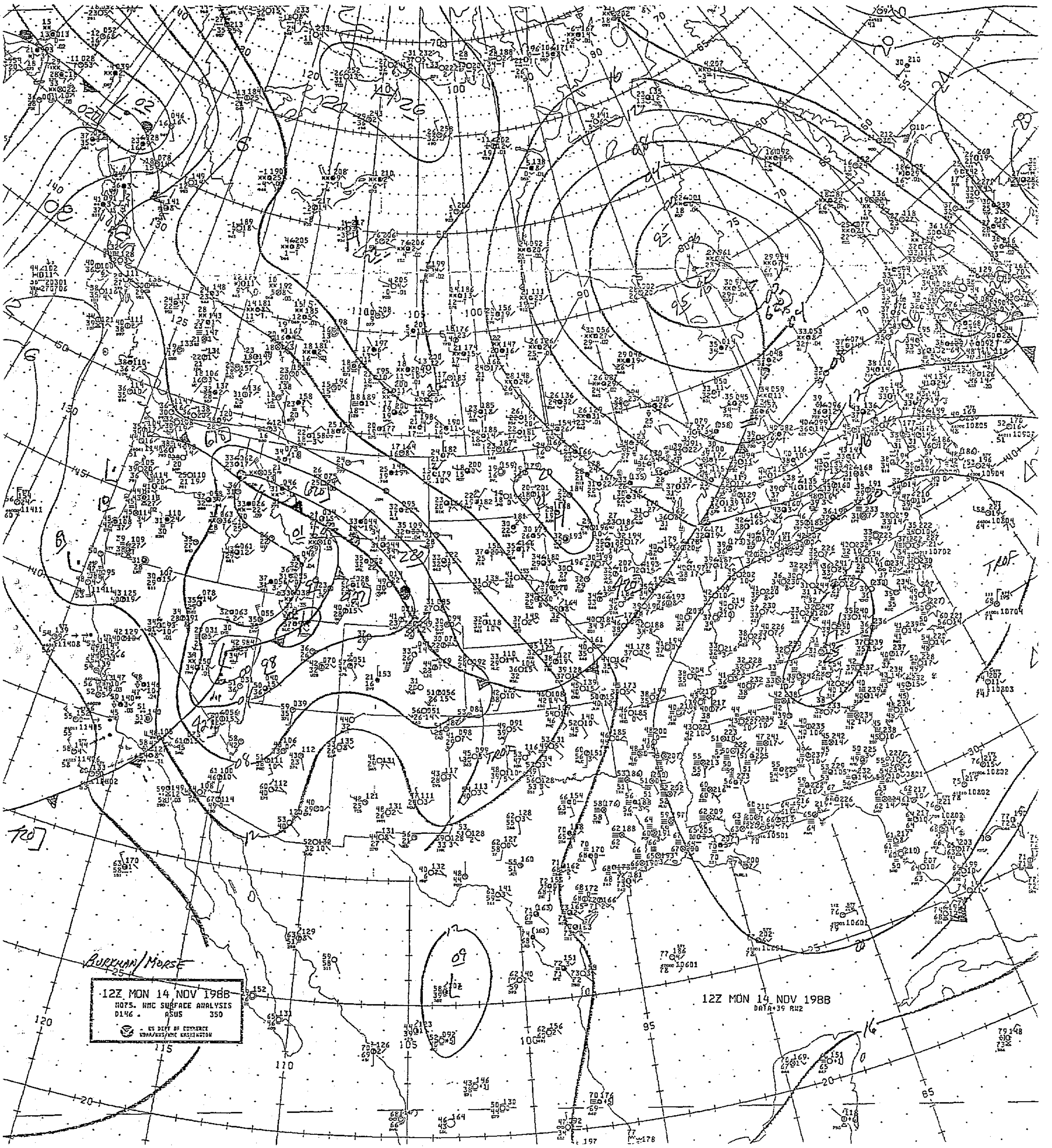


Fig. 11. A section of the NMC surface analysis for 1200 UTC 14 November 1988 (12 h verification time of the forecasts shown in Fig. 12).

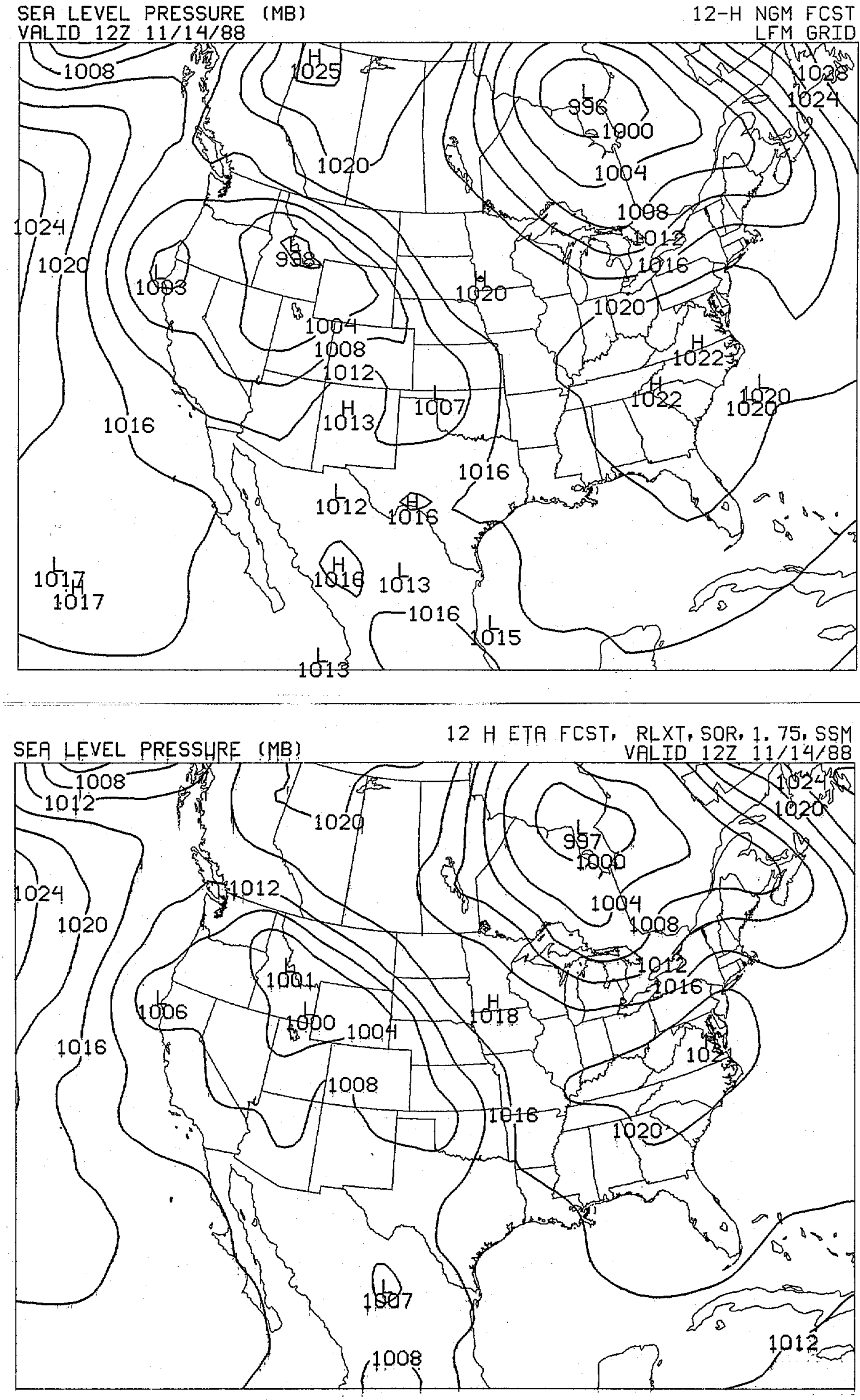


Fig. 12. Sections of the NGM (upper panel) and eta (lower panel) sea level pressure 12 h forecasts verifying at 1200 UTC 14 November 1988.

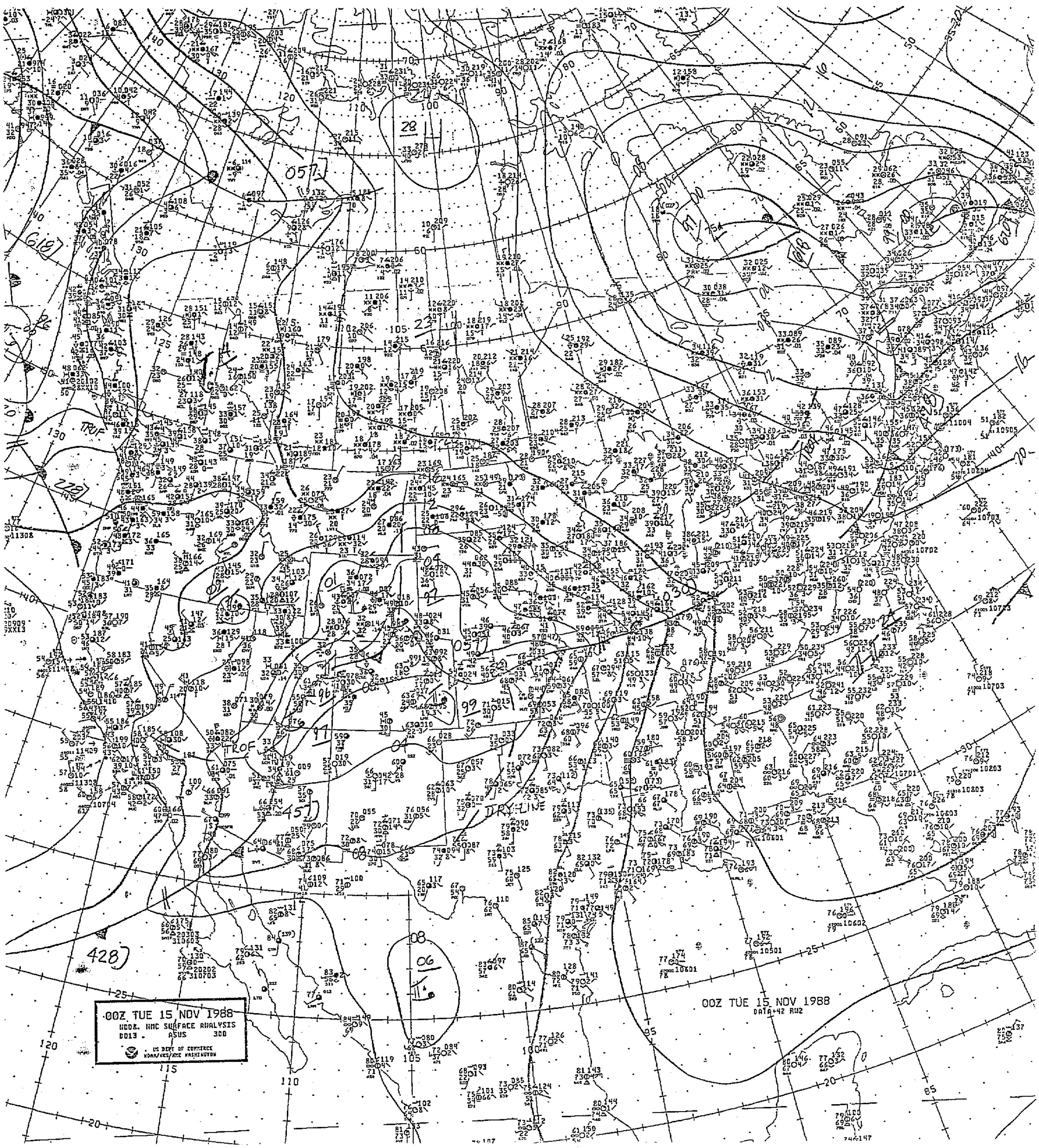


Fig. 13. A section of the NMC surface analysis for 0000 UTC 15 November 1988 (24 h verification time of the forecasts shown in Fig. 14 and in the upper panel of Fig. 19).

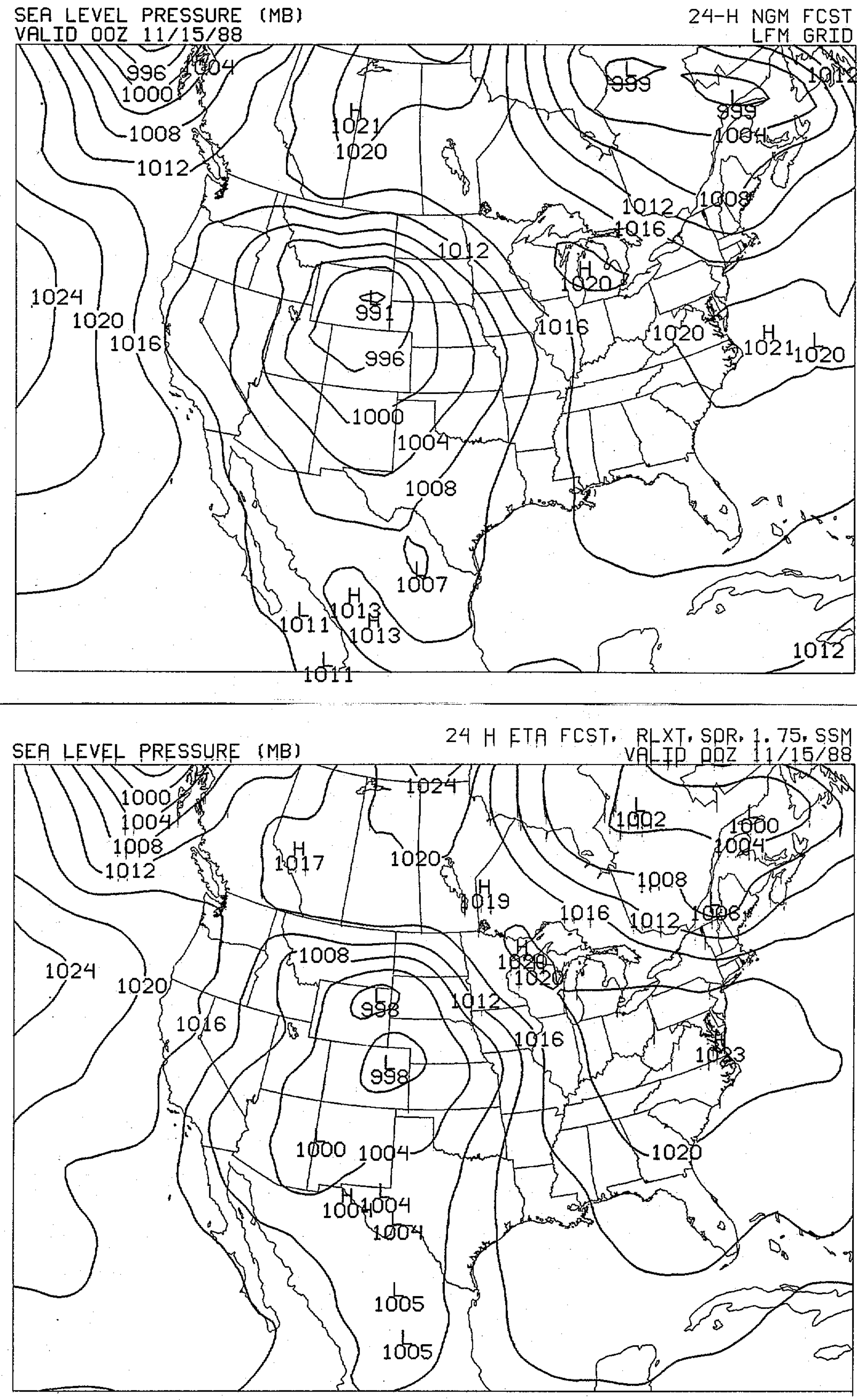


Fig. 14. Sections of the NGM (upper panel) and eta (lower panel) sea level pressure 24 h forecasts verifying at 0000 UTC 15 November 1988.

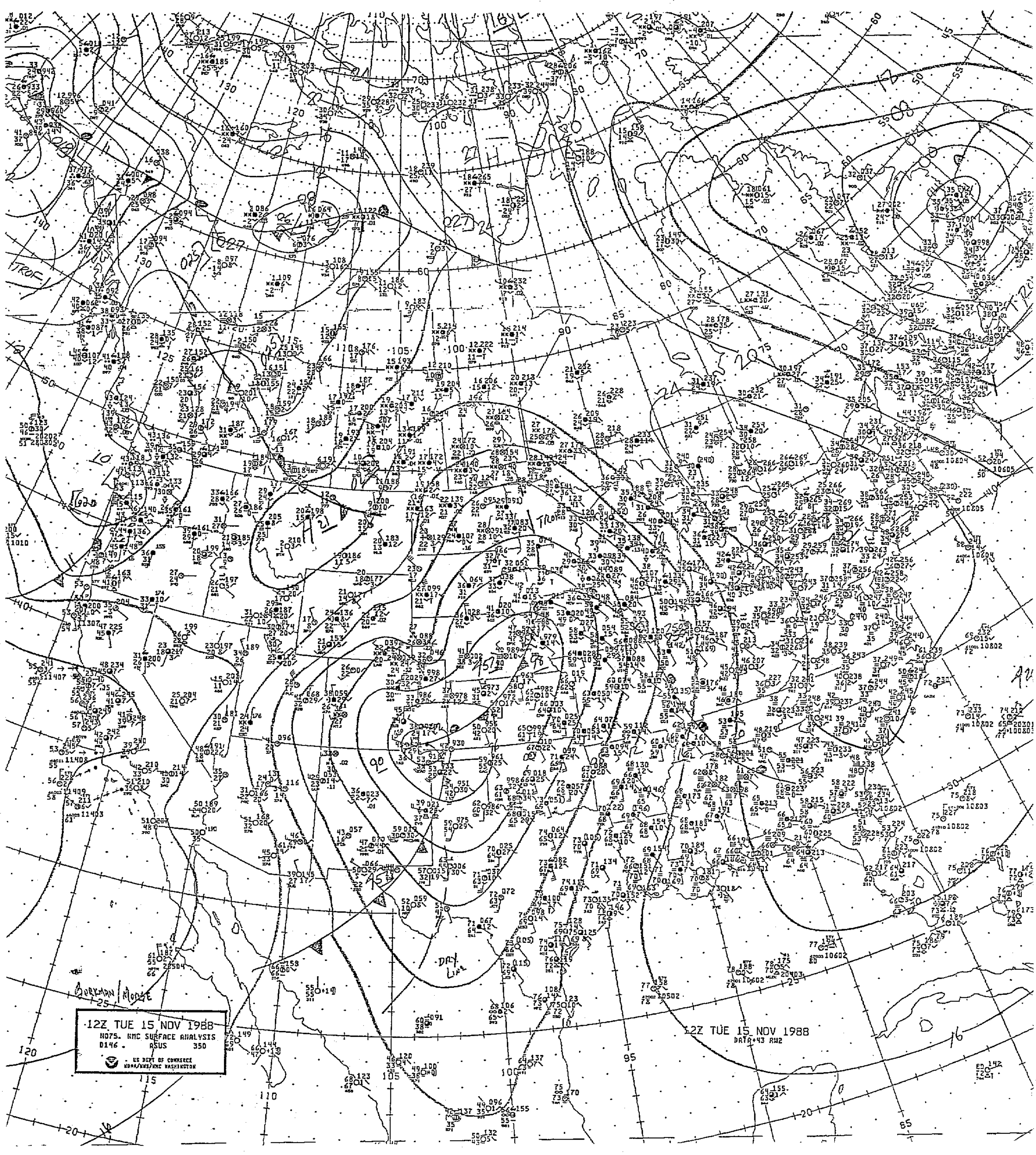


Fig. 15. A section of the NMC surface analysis for 1200 UTC 15 November 1988 (36 h verification time of the forecasts shown in Fig. 16).

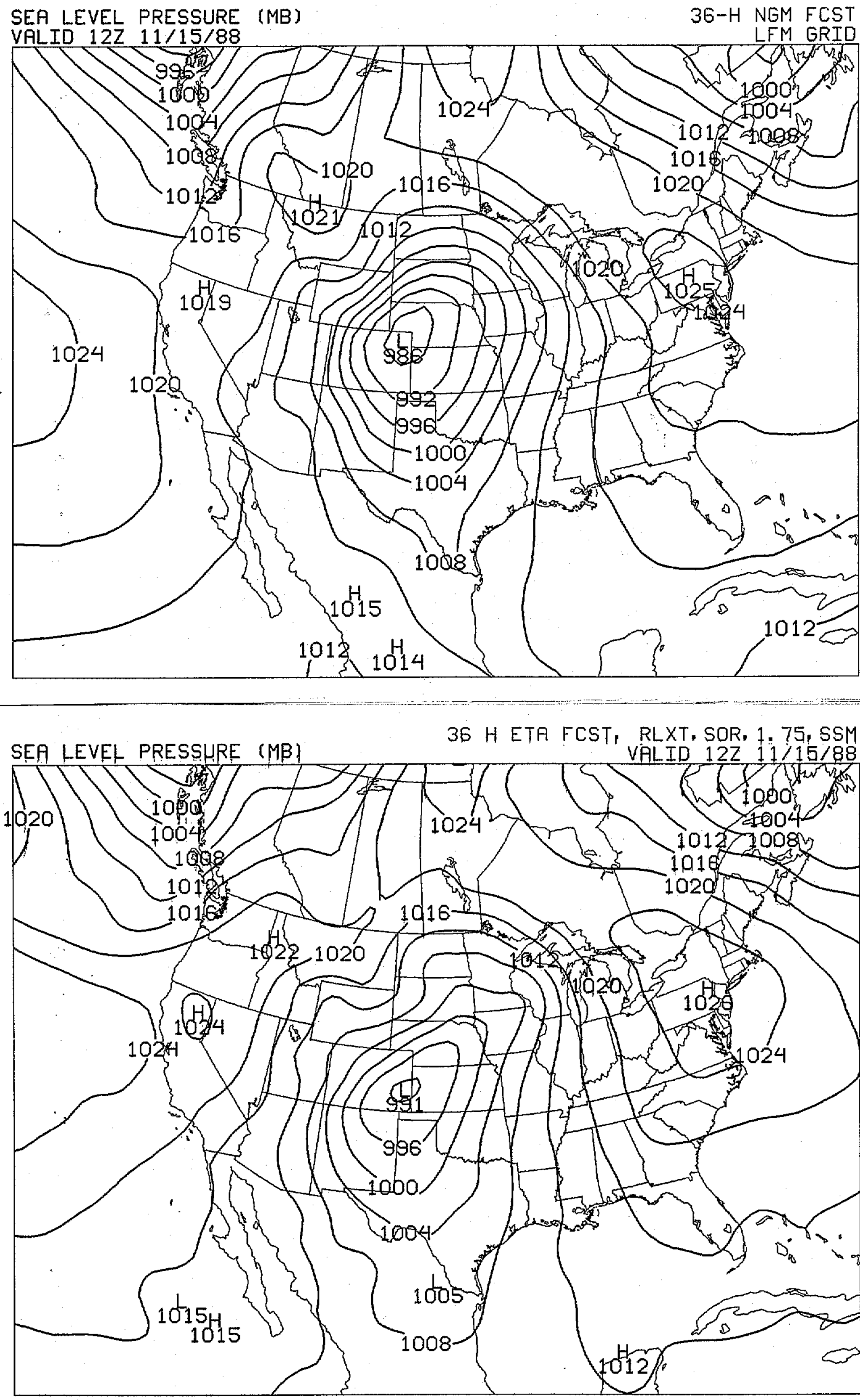


Fig. 16. Sections of the NGM (upper panel) and eta (lower panel) sea level pressure 36 h forecasts verifying at 1200 UTC 15 November 1988.

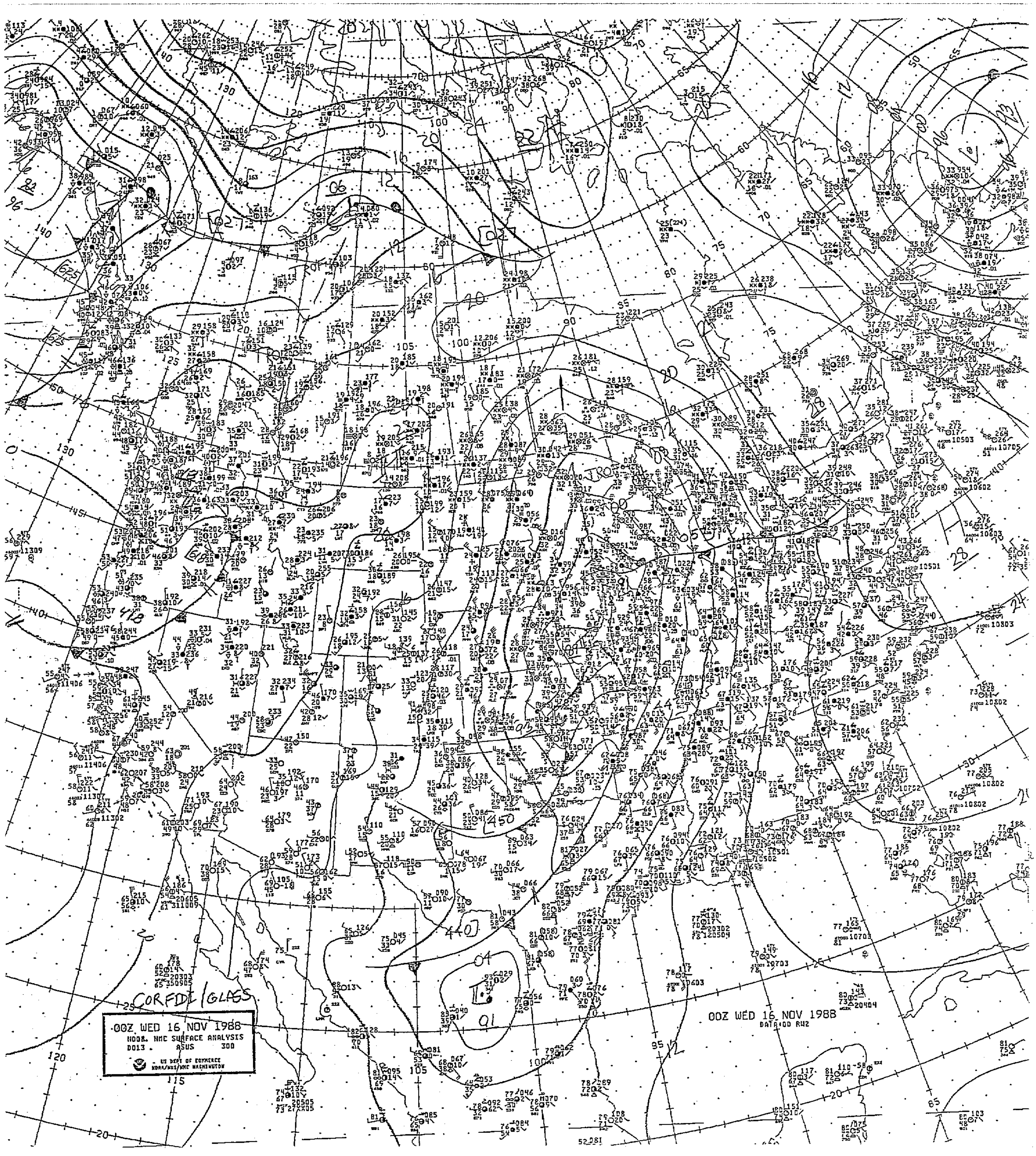


Fig. 17. A section of the NMC surface analysis for 0000 UTC 16 November 1988 (48 h verification time of the forecasts shown in Fig. 18 and in the lower panel of Fig. 19).

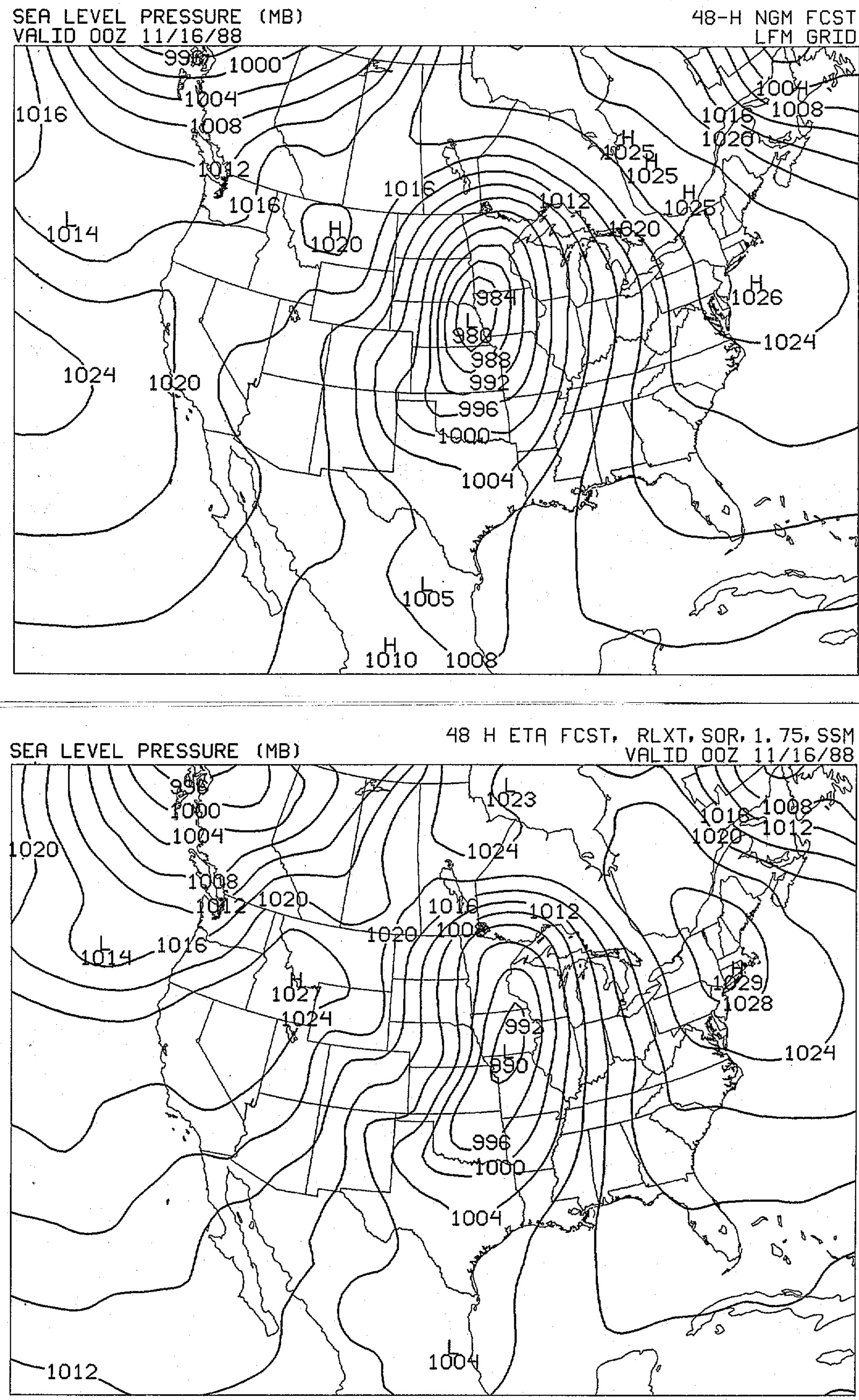


Fig. 18. Sections of the NGM (upper panel) and eta (lower panel) sea level pressure 48 h forecasts verifying at 0000 UTC 16 November 1988.

for the categories of 1.25 inches and greater where the eta model showed some skill as opposed to practically no skill shown by the NGM model.

As for the overall amounts, both models underforecast the higher amounts of precipitation, the NGM more so than the eta model. On the other hand, both models overforecast the very light amounts of precipitation, the eta model more so than the NGM. We speculate that this latter weakness, and perhaps also the tendency of the models to underforecast the total amounts, is the consequence of the absence of cloud water as a prognostic variable. With no cloud water, condensation immediately results in precipitation which must produce too frequent light precipitation but also regarding intense rain could result in more widespread rather than concentrated patterns.

In comparing the 500 mb geopotential height errors the aviation model was also included. A problem with these comparisons however was that for archiving reasons it was not possible to verify each of the three models against its own initial heights. It is expected that this will be possible in the near future. In the meantime NGM initial heights were chosen as verification for all three of the models. For the 30 days of November, the aviation model had the smallest standard deviation and also the smallest total rms height errors. The eta model, on the other hand, had the smallest mean error and beyond 12 h had also the standard deviation of the errors smaller than the NGM.

Planned work to further improve the eta model's performance includes incorporation of more detailed surface processes and carrying cloud water explicitly.

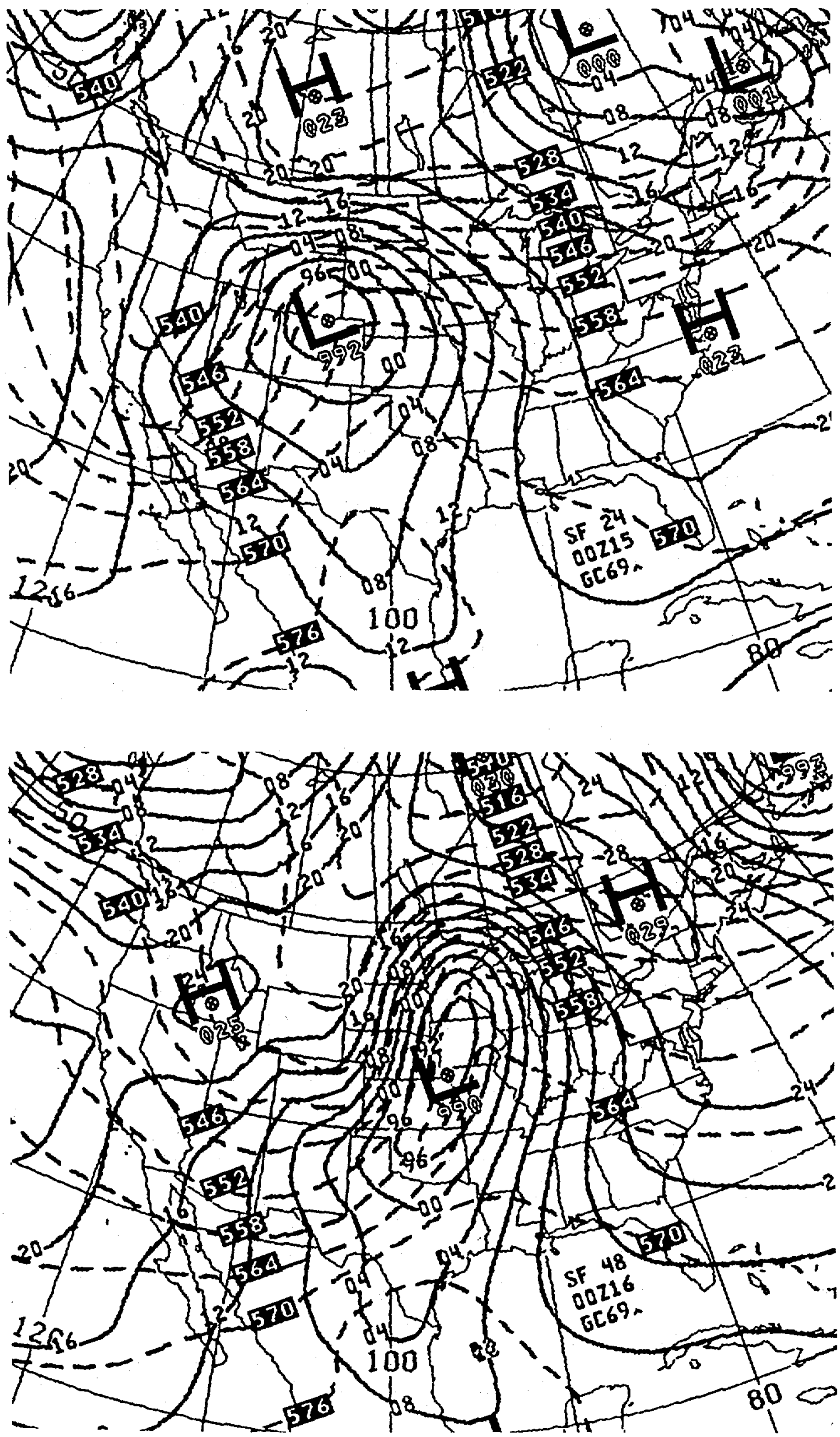


Fig. 19. Sections of the 24 h (upper panel) and 48 h (lower panel) MRF sea level pressure and 1000/500 mb thickness forecasts verifying at the same time as forecasts shown in Fig. 14 and Fig. 18, respectively.

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